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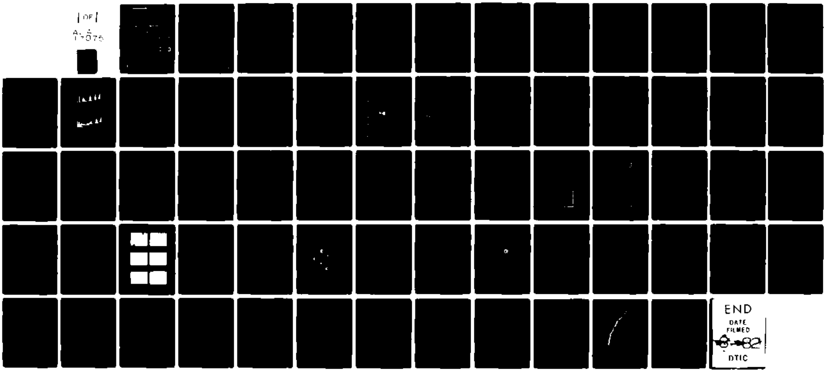

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AFOSR-TR- 82-0514

1982

AFOSR

RESEARCH MEETING

ON

DIAGNOSTICS OF REACTING FLOW

25-26 FEBRUARY 1982

STANFORD UNIVERSITY

STANFORD, CALIFORNIA

UNCLASSIFIED

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PROPULSION	AIRBREATHING ENGINES
SPECTROSCOPY	TEMPERATURE MEASUREMENT
DIAGNOSTICS	SPECIES MEASUREMENT
REACTING FLOW	VELOCITY MEASUREMENT

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This document contains expanded abstracts from the 1982 meeting on the Air Force basic research program on diagnostics of reacting flow. The meeting (held at Stanford University on 25 - 26 February 1982) presented research directed at measuring temperatures, velocities, and concentrations in high performance combustion environments.

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PREFACE

This is a one-time-only meeting for the purpose of coordinating the several aspects of the research which has been initiated as part of the new AFOSR task entitled Diagnostics of Reacting Flow (2308/A3). Since the meeting is intended to promote interactions among the researchers on specific issues, the attendance is limited to 40 people actively involved in Air Force sponsored research. Other meetings provide ample opportunities to coordinate with the counterparts in other agencies. The host for the meeting is Prof. Ronald K Hanson, who is the Principal Investigator for the multi-discipline research program at Stanford University.

The meeting includes presentations from both the AFOSR, AFRPL, and AFAPL basic research programs. Thus, during the two days, the attendees will be able to gather a reasonably complete picture of the Air Force research program on diagnostics of reacting flows.

We are using a very specific format for the abstracts. The body of each abstract begins with a short statement of relevant scientific questions addressed by the research, followed by an explanation of the approach. A statement of the uniqueness of each approach was solicted. The major portion of the text is devoted to a discussion of results obtained since last years meeting. The abstracts describe two figures: Figure 1 illustrates the main features of the approach and Figure 2 presents a primary accomplishment.

Hard copies of the vugraph material and backup information are in file folders (one for each presentation) which are placed on a table at the rear of the meeting room. Thus, it can be referred to by anyone in the audience either before or after the presentations.

One of the primary objectives of this meeting is to encourage the attendees to consider new research approaches. Several of the presentations are intended to give guidance on research directions for the next five to ten years. Encouragement is given to bold approaches to the most challenging goals. However, responses of prospective principal investigators should not be limited by the stated goals. The location of this meeting promotes interchanges among the attendees by being held near organizations interested in this research. Of course, the attendees are encouraged to establish communications with their technical counterparts within the Air Force. Also, questions can be directed to:

Leonard H Caveny
AFOSR/NA
Bolling AFB
Washington, DC 20332
(202) 767-4937 or AV297-4937

1982 AFOSR RESEARCH MEETING ON DIAGNOSTICS OF REACTING FLOWS

STANFORD UNIVERSTIY
Stanford, CA

Thursday
25 February 1982

TIME	NUM.	
0830		REGISTRATION - Durand Building, 4th Floor
		SESSION CHAIRMAN: Leonard H Caveny, AFOSR/NA
0900		ANNOUNCEMENTS
0905	1	OVERVIEW OF STANFORD PROGRAM ON ADVANCED DIAGNOSTICS FOR REACTING FLOWS. Ronald K Hanson, C Thomas Bowman, Sidney A Self, Robert L Byer, Donald Baganoff, Brian J Cantwell, and Lambertus Hesselink, Stanford University, Stanford, CA
0920	2	SPECIES MEASUREMENTS BY TUNABLE LASER ABSORPTION TECHNIQUES. Ronald K Hanson, Stanford University, Stanford, CA
0940	3	CARS. Robert L Byer, Stanford University, Stanford, CA
1000	4	SPECIES AND TEMPERATURE MEASUREMENTS DURING SOLID PROPELLANT COMBUSTION. David P Weaver, AFRPL/DYP
1030		BREAK (15 minutes)
1045	5	RESONANT CARS DETECTION OF OH RADICALS. James F Verdieck, Robert J Hall, and Alan C Eckbreth, United Technology Research Center, East Hartford, CT
1115	6	COMBUSTION DIAGNOSTICS AT THE AEROPROPULSION LABORATORY. Mel Roquemore, Royce P Bradley, J S Stutrud and C M Reeves, AFAPL/POSF
1145	7	OVERVIEW: AFOSR RESEARCH INTERESTS IN DIAGNOSTICS OF REACTING FLOWS. Leonard H Caveny, AFOSR/NA
1200		LUNCH at Stanford Faculty Club (Reconvene at 1330)

(23 Dec 1981/LHC 0136G)

Thursday PM
25 February 1982

Session Chairman: Donald Stull, AFAPL/PORT

TIME	NUM.	
1330	8	COHERENT OPTICAL SPECTOSCOPY IN FLAME. John W Daily, University of California, Berkeley, CA
1400	9	CHARACTERIZATION OF TURBULENT FLAMES. Michael C Drake, Marsnall Lapp, C Murray Penney, and Robert W Pitz, General Electric Research Laboratories, Schenectady, NY
1430	10	NOISE THERMOMETRY IN COMBUSTION PROCESSES. Stephen P Gill and John D Watson, Artec Associates, Haywood, CA.
1500		BREAK
1515	11	AFRPL INTERESTS IN DIAGNOSTICS OF ROCKET MOTOR PROCESSES. David M Mann, AFRPL/XRX
1530	12	AFAPL RESEARCH INTERESTS IN DIAGNOSTICS OF AIR BREATHING ENGINE PROCESSES. Donald Stull, AFAPL/PORT
	13	*X-RAY MEASUREMENT OF SPECIES IN TWO-PHASE FLOWS. Jay D Eversole, University of Dayton Research Institute, Edwards AFB, CA
1545		[** meeting highlight 1 ** five invited perspectives (about 5 minutes each) followed by open discussion on areas and topics of coordination, purposeful overlap, etc. Also, discussion will introduce the unique opportunities presented by the Air Forces space propulsion and power initiatives.]
1645		ADJOURN SESSION
1645		ADMINISTRATIVE MEETING FOR AFOSR CONTRACTORS
1715		ADJOURN ADMINISTRATIVE MEETING
1730		Social Hour - Stanford Faculty Club, Red Lounge
1900		Dinner - Stanford Faculty Club (Cost included in registration fee, as an option.)

*Presentation will not be made but vugraph material is available at rear of meeting room.

Friday
26 February 1982

TIME	NUM.	
0820		REGISTRATION - Durand Building, 4th Floor
		SESSION CHAIRMAN: Howard R Schlossberg, AFOSR/NP
0830	14	STUDY OF EVAPORATING FLOW USING LASER-INDUCED FLUORESCENCE. Donald Baganoff and Brian Cantwell, Stanford University, Stanford, CA
0845	15	PACKAGED, FIBER-OPTIC SPECTRORADIOMETER. Sidney Self, Stanford University, Stanford, CA
0915	16	PARTICLE SIZE DISTRIBUTION AND VELOCITY VIA NUMERICAL HOLOGRAPHIC RECONSTRUCTION. Richard V Denton, and Hassan Mostafavi, TAU Corporation, Los Gatos, California
0930	17	DETERMINATION OF LIQUID DROPLET EVAPORATION RATES IN A SPRAY BY INELASTIC LIGHT SCATTERING. Richard K Chang, Marshall B Long, and Boa-Teh Chu, Yale University, New Haven, CT
1000	18	MAGNETIC FIELD COUPLED VELOCIMETERS. Carl Spight, AMAF, Inc, Columbia, MD
1030		15 minute break
1045	19	MULTIANGULAR SCANNING ABSORPTION TECHNIQUES FOR THREE DIMENSIONAL COMBUSTION DIAGNOSTICS. Robert Goulard , George Washington University, Washington, DC
1115	20	COMPUTED ABSORPTION TOMOGRAPHY. Robert L Byer, Stanford University, Stanford, CA
1130	21	QUANTITATIVE FLOW VISUALIZATION. Ronald K Hanson, Stanford University, Stanford, CA
1145	22	THREE DIMENSIONAL FLOW VISUALIZATION. Lambertus Hesselink, Stanford University, Stanford, CA
1200	23	MEASUREMENTS IN TURBULENT REACTING FLOWS. Craig T Bowman, Stanford University, Stanford, CA
1215		LUNCH at Stanford Faculty Club (reconvene at 1345)

Friday PM
26 February 1982

Session Chairman: Leonard H Caveny, AFOSR/NA

TIME NUM.

1345 [** meeting highlight 2 ** Topic: Research accomplishments: real or imagined? This will be an open discussion on the perception of basic research payoffs with respect to propulsion and energy conversion challenges.]

1415 [** meeting highlight 3 **] Demonstration of advanced diagnostics experiments in progress at Stanford University.

OVERVIEW OF STANFORD PROGRAM ON ADVANCED DIAGNOSTICS FOR REACTING FLOWS

Ronald K. Hanson, C. Thomas Bowman, Sidney A. Self, Robert L. Byer*
Donald Baganoff†, Brian J. Cantwell†, and Lambertus Hesselink†

Mechanical Engineering Department
*Applied Physics Department
†Aeronautics and Astronautics Department
Stanford University, Stanford, CA 94305

ABSTRACT

Increasing demands on Air Force combustion systems and rapid advances in instrumentation technology have combined to stimulate considerable interest in the development of modern, primarily laser-based diagnostics for combustion research. This presentation will provide an overview of work recently initiated at Stanford, under the sponsorship of AFOSR, to develop, validate and apply promising new diagnostic techniques for measurements in reacting flows.

The Stanford program is a relatively large, interdisciplinary effort involving seven faculty in three departments. The various research topics have been selected to provide a spectrum of activities, ranging from fundamental to applied research. Generally, the objective is to provide improved measurement capabilities for quantitative visualization of flows and for determining quantities such as species concentration, temperature, particle size, particle number density and velocity, preferably with high spatial and temporal resolution. Projects to develop techniques for measuring and displaying flow parameters in a plane or throughout an extended volume are included, as are projects to apply newly developed techniques to selected flows of fundamental interest.

The objective of this presentation will be to introduce the Stanford program and to encourage useful interactions with other researchers interested in diagnostics development. Current research topics are listed in Figure 1 (see following pages) together with a statement indicating the quantities to be determined.

- TUNABLE LASER ABSORPTION/FLUORESCENCE PROBES (Hanson) - Development of absorption and fluorescence techniques for spatially and temporally resolved species or temperature measurements using tunable (IR, visible and UV) laser sources and either intrusive optical fiber probes or fast-sampling probes with miniature in-line measurement cells.

- CROSSED-BEAM CONCEPTS (Hanson) - Development of techniques for spatially resolved species measurements by modulated absorption of a weak tunable UV or IR laser probe beam crossed with a strong tunable laser pump beam operating resonant (saturated absorption) or non-resonant (ac-Stark effect) with the probe beam.

- COMPUTED ABSORPTION TOMOGRAPHY (Byer) - Development of techniques for measuring species concentration, density or temperature in a plane using multiple observations and computer deconvolution methods.

- COHERENT ANTI-STOKES RAMAN SPECTROSCOPY (Byer) - Development of techniques and measurements of species concentration, temperature, velocity and fundamental spectroscopic parameters using various novel CARS configurations.

- PARTICLE SIZING (Self) - Development of particle size measurement techniques using two-color transmissometry and a wire-filter sampling probe.

- PACKAGED FIBER OPTIC TEMPERATURE PROBE (Self) - Development of a compact, portable instrument, based on the line reversal concept, for fast response temperature measurements in seeded combustion flows.

- QUANTITATIVE FLOW VISUALIZATION (Hanson) - Development of techniques for spatially and temporally resolved measurements of species, temperature or velocity in a plane using novel variations of laser-induced fluorescence.

- THREE-DIMENSIONAL FLOW VISUALIZATION (Hesselink) - Development of a novel holographic technique for the 3-d display of species, temperature or velocity data obtained from a family of cross-sectional (planar) data sets or observations.

- MEASUREMENTS IN A TURBULENT REACTING FLOW (Bowman) - Development and characterization of a 2-d turbulent reacting shear flow facility, and the development and application of diagnostics for studying turbulent flowfield structures.

- EVAPORATING FLOW STUDIES (Baganoff and Cantwell) - Assembly and characterization of a new facility for studies of droplet evaporation in laminar and turbulent flows, and the development of techniques, based on laser fluorescence and anemometry concepts, for monitoring the liquid and gas phases in a droplet-laden flow.

Figure 1. Current Research Topics

SPECIES MEASUREMENTS BY TUNABLE LASER ABSORPTION TECHNIQUES

Ronald K. Hanson

Mechanical Engineering Department
Stanford University
Stanford, California 94305

This research seeks to provide sensitive, species specific techniques for monitoring gaseous concentrations in reacting flows. The development of such techniques has the potential for significant impact on various scientific and engineering aspects of combustion and propulsion. One promising approach, which has been pursued particularly at Stanford, utilizes absorption spectroscopy as the sensing process and seeks to combine recently developed tunable laser sources with a variety of novel absorption probes, including configurations yielding high spatial resolution. The resulting diagnostics appear well suited to meet a variety of practical and fundamental measurement requirements.

The program includes several related research projects, ranging from work to provide improved laser sources, to exploration of new sensing phenomena or probe configurations, to demonstration of promising techniques in laboratory combustion flows. A summary of current projects is given below. One project, aimed at developing and demonstrating a tunable IR laser absorption probe enabling continuous recording of spatially resolved species concentration, is highlighted in Figs. 1 and 2.

Tunable UV/Visible Techniques (cw ring dye laser)

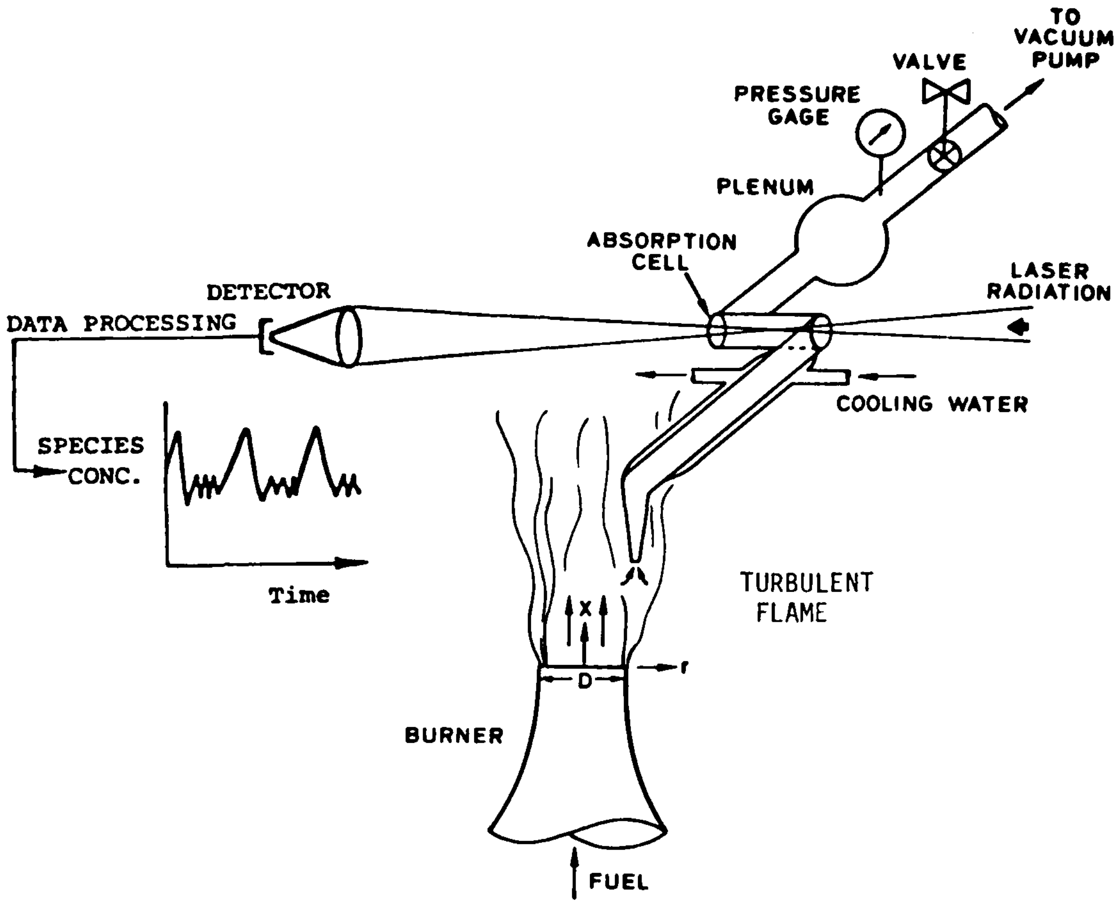
- development of a fiberoptic absorption/fluorescence probe
- development of an external resonator for high efficiency frequency doubling of cw ring dye laser
- development of fiberoptic links for remote absorption measurements in a shock tube and a combustion tunnel
- investigation of off-resonance laser fluorescence for reduced sensitivity to quenching

Tunable IR Techniques (cw diode laser)

- development and validation of a variable pathlength (Light Guide) probe for continuous, real-time species measurements
- development and validation of a fast-sampling probe with an in-line absorption cell for continuous, real-time species measurements

Crossed-Beam, Modulated Absorption Techniques (cw ring dye laser, cw diode laser, pulsed YAG/dye laser)

- studies of beam interactions using resonant (saturated absorption) and non-resonant (ac-Stark effect) pump and probe laser sources.



Objective:	Develop sampling probe with in-line absorption cell for temporally and spatially resolved species measurements using a tunable IR diode laser source
Status:	Second-generation probe has been built and feasibility demonstrated in turbulent CO/air diffusion flame Spatial resolution ~5 mm; Bandwidth > 1 kHz
Disadvantage:	Intrusive
Advantages:	Superior sensitivity and accuracy Yields continuous, real-time concentration Applicable where optical access is restricted Well-suited for use as remote detector using fiberoptic link

Figure 1. Laser absorption sampling probe for temporally and spatially resolved species measurements in reacting flows.

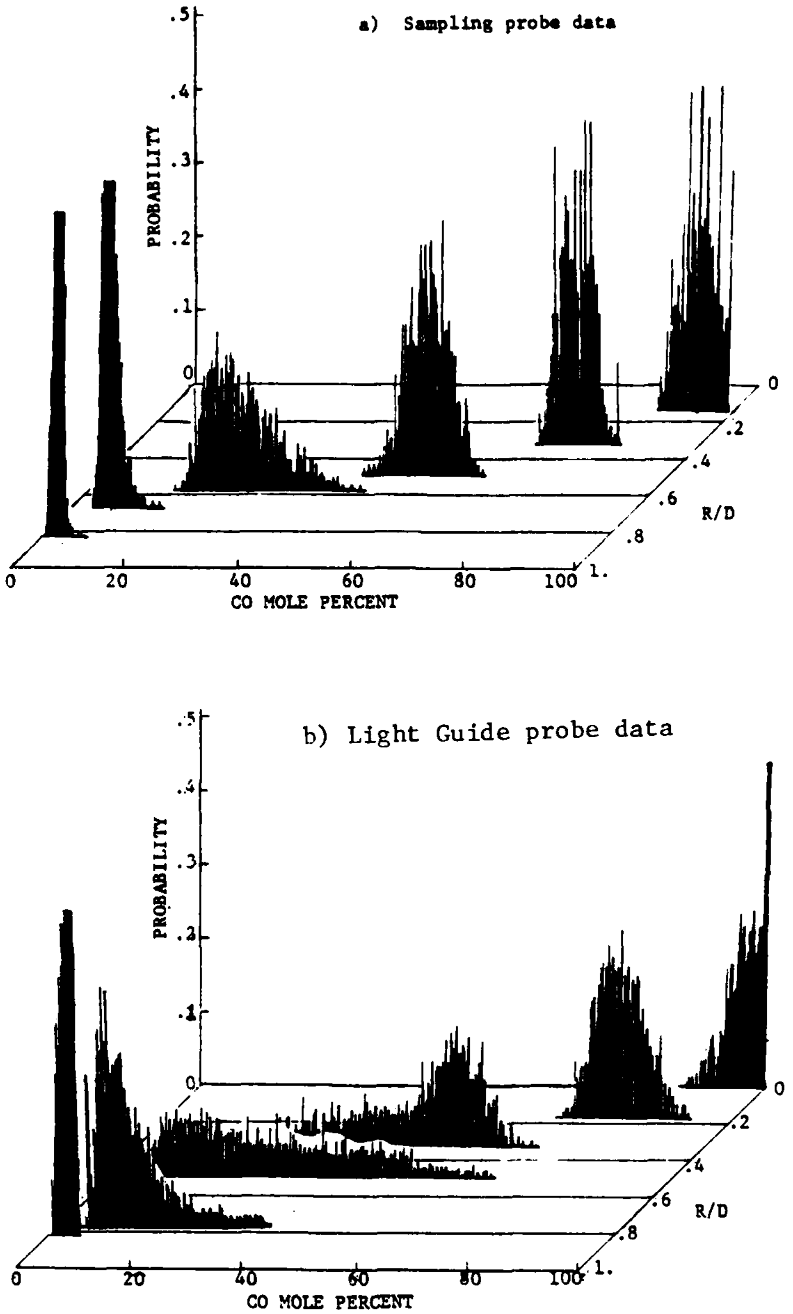


Figure 2. Radial map of probability density functions of CO mole percent in the CO/air diffusion flame at an axial position X/D = 2. a) Based on sampling probe data, b) based on Light Guide probe data.

COHERENT ANTI-STOKES RAMAN SPECTROSCOPY

Robert L. Byer
Applied Physics Dept.,
Stanford University

We have used high resolution CARS spectroscopy of methane in a supersonic molecular expansion) to measure the flow velocity and temperature profile of the expansion.[1,2] The approach is unique in that the flow parameters were measured without the need for seeding. The microscopic volume probed by the focused laser beams allowed a small supersonic expansion to be studied at excellent spatial resolution.

The study led to the first observation of transet time broadening in a Raman spectroscopy experiment and to the development of the theory of transet time broadening in a CARS process.

The experimental apparatus, shown in Fig. 1, illustrates the major components of the velocity measurement apparatus. A cw dye laser with 100 mW of power is tuned to the Stokes wavelength relative to the single frequency 2W argon ion laser line at .5145 μm. The beams are combined and collinearly focused into the expansion, recollimated, spectrally selected for the anti-Stokes and detected.

Figure 2 illustrates the CH_4 Q-branch spectrum and the geometry of the jets used to measure the velocity components. The measured velocity agreed with the theoretically calculated velocity to within 4%. The temperature was determined by fitting the rotational components of the spectrum. The temperature was measured to $\pm 1^{o}K$.

REFERENCES

1. E.K. Gustafson, J.C. McDaniel and R.L. Byer, "CARS Measurement of Velocity in a Supersonic Jet", IEEE Journ. Quant. Electr. QE-17, p.2258 (1981).

2. E. Gustafson, J. McDaniel and R.L. Byer, "Continuous Wave CARS Measurements in a Supersonic Jet", IEEE Journ. Quant. Electr. vol. QE-17, p.62, December 1981. (Presented at the 1981 C.L.E.O. Conference, Washington D.C.).

3. E. Gustafson and R.L. Byer, "Transet Time Linewidth Limitations in cw CARS Spectroscopy", (submitted to I.Q.E.C. Conference to be held in Munich, Germany, June 1982).

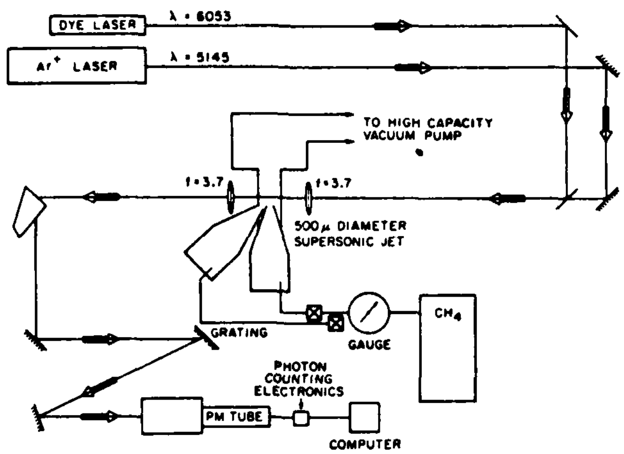
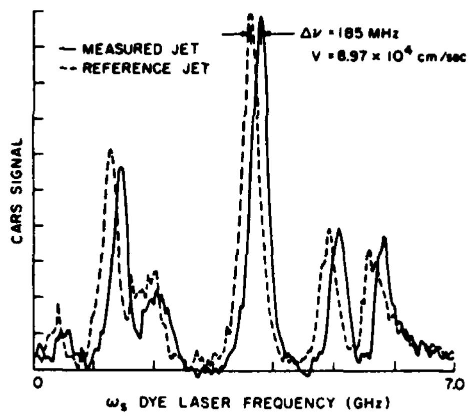
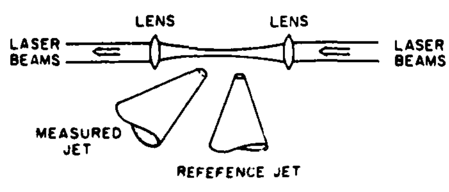


Fig. 1. Experimental apparatus.



(a)



(b)

Fig. 2. (a) Spectra taken in supersonic jet. The dashed line is the spectrum from the reference jet. The solid line is the spectrum taken in the jet whose velocity is to be measured. (b) Jet apparatus. The vertical jet is the reference jet. The tilted jet has a velocity component in the direction of the laser beams.

RESONANT CARS DETECTION OF OH RADICALS

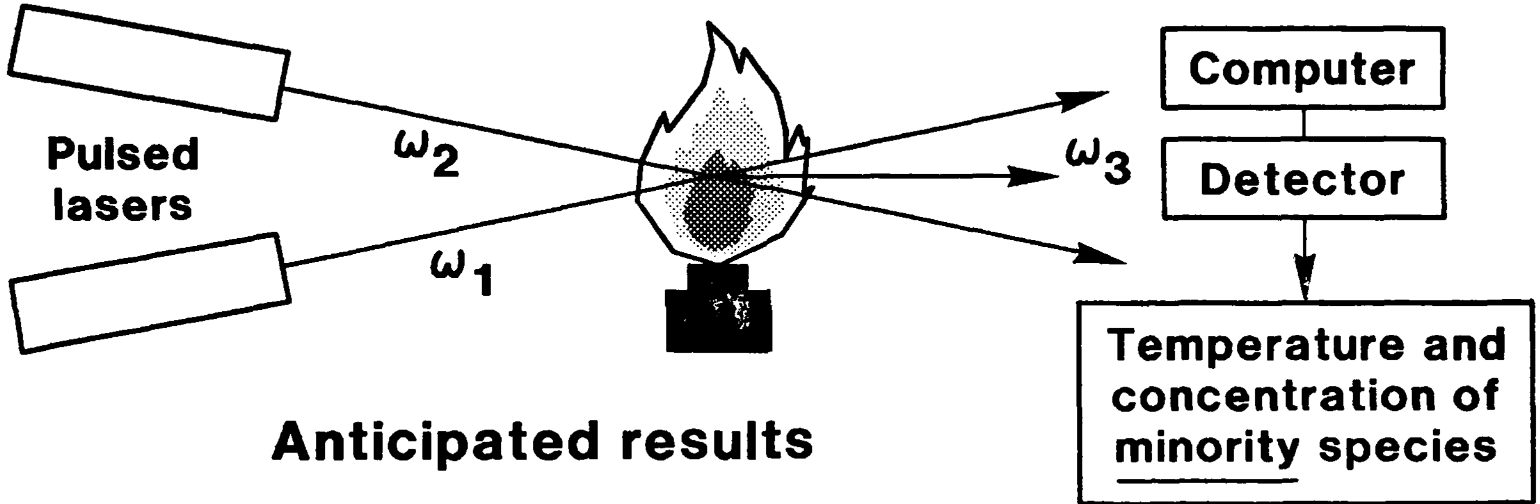
James F. Verdieck, Robert J. Hall and Alan C. Eckbreth
United Technologies Research Center, E. Hartford, Ct.

The major objective of this research is to establish the applicability of the highly successful CARS diagnostic technique to the detection and measurement of OH radicals. Preliminary experiments in a near stoichiometric H_2/O_2 flame indicate that OH can be detected by coventional CARS; however, in spite of the exceptionally high concentration of OH in such a flame ($\sim$ 10%), the OH CARS spectrum appears on the tail of the H_2O CARS spectrum. Because of this spectral interference from water and the fact that OH may have much lower concentrations in most situations, resonantly enhanced CARS offers a means of improving detectivity, by an order of magnitude or better.

CARS diagnostics has been demonstrated to be uniquely suited for combustion studies because it is a remote, non-perturbing, spatially and temporally precise, accurate means of measuring temperature and concentration of major combustion species in-hostile environments. The extension of the CARS diagnostic method to minority species such as OH would be an important advance in combustion research. Resonant CARS will be sought for in OH by application of two tunable UV dye lasers, one of which will be selected to be resonant with an electronic transition in OH. The other dye laser will be tuned to generate the CARS spectrum. The degree of CARS signal enhancement will be measured relative to normal CARS. The possibility of achieving a triple resonance (one vibrational-rotational resonance, two electronic resonances) will be assessed by computer analysis of OH energy levels. This may be desirable in obtaining further enhancement of the CARS signal.

Initially, an attempt to observe the OH CARS spectrum without resonant enhancement was performed in a hydrogen/oxygen flame. For this purpose a multi-element capillary tube diffusion flame burner was constructed and tested. The flame produced is very uniform, much like a premixed flame, at distances more than one inch above the burner. Conventional CARS spectra of water and OH were taken in this burner at several positions and with different H_2/O_2 flows. The next steps of this program will be to construct the tunable dye lasers and obtain frequency doubled output in the UV. Attempts to observe resonant CARS in OH will then follow. Because water is an inevitable companion of OH in a combustion process, a chemical titration technique ($H+NO_2 \rightarrow OH+NO$) will be set up to observe the OH CARS spectrum without water present.

INVESTIGATIONS OF RESONANT CARS DETECTION OF OH RADICALS



Anticipated results

- Enhance CARS detectivity by > 10^2
- Permit CARS measurements of minority species ($c < 0.1\%$)
- Obtain spatially precise radical concentration and temperature measurements in combustion zone

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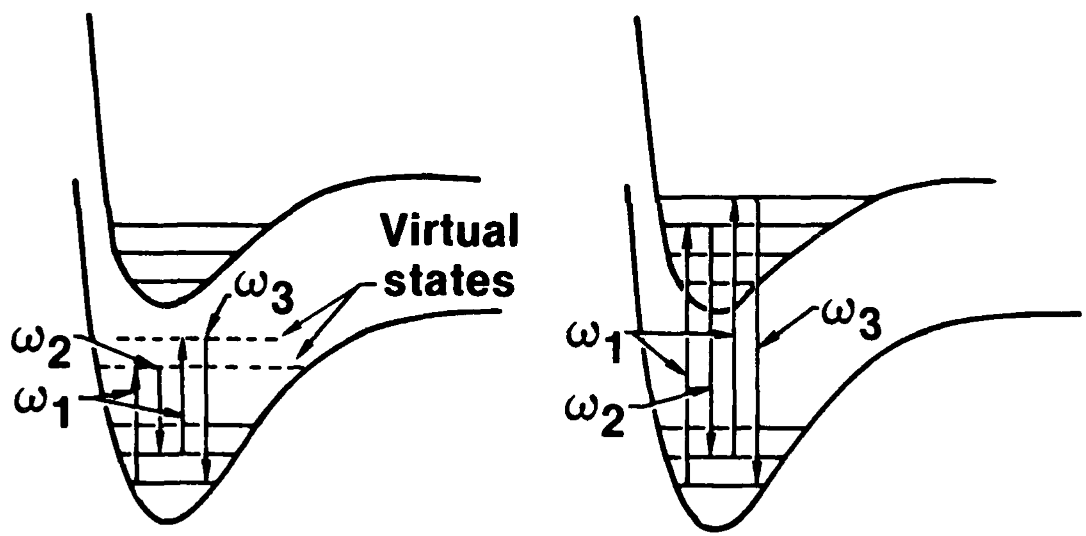
FIGURE I
Abstract 5
Page 2

INVESTIGATION OF RESONANT CARS DETECTION OF OH RADICALS

Scientific approach

Resonant CARS



Singly (vib-rot) resonant CARS

Doubly (electronically enhanced) resonant CARS

- Design experiment, make initial tests
- Demonstrate resonant CARS in OH
- Optimize resonant signal enhancement

RA135.001

FIGURE 2

Abstract 5
Page 3

COMBUSTION DIAGNOSTICS AT APL

MEL ROQUEMORE, ROYCE P. BRADLEY, J. S. STUTRUD AND C. M. REEVES

AERO PROPULSION LABORATORY

WRIGHT-PATTERSON AIR FORCE BASE, OHIO

A program in the Fuels Branch of the Aero Propulsion Laboratory (APL) involves the development and evaluation of diagnostic techniques for making time averaged and time resolved point measurements of velocity, temperature and major species concentration in a research combustor at APL. Conventional techniques such as thermocouples and gas sampling probes as well as nonintrusive optical techniques such as laser Doppler anemometry (LDA), coherent anti-Stokes Raman scattering (CARS), and spontaneous Raman scattering are being investigated. Flame radiation measurements and high speed motion pictures are also being used to study combustion processes.

The primary objective of this program is to use the appropriate diagnostic techniques to collect data in an APL research combustor for the purpose of evaluating and developing combustion models. The program is a composite of several efforts involving both contractor and government participation. The University of Dayton Research Institute is responsible for the LDA, spontaneous Raman, and high speed laser shadowgraph systems and for model evaluations. Systems Research Laboratories is responsible for CARS development and utilization. APL is responsible for program management, facility operation, conventional probe measurements, flame emissions measurements, data analysis and data compilation. The objective and approach are illustrated in Figure 1.

The program has been in progress for about three years. Much of this time has been spent in developing the combustion facility and the laser diagnostic techniques to be used in the facility. The most notable accomplishments include: the development of a semiquantitative understanding of the time averaged flow field for different combustor operating conditions, the compilation of a data package consisting of inlet radial profiles and centerline profiles of axial velocities for both cold and combusting flows, comparisons of velocity data with FREP and TEACH code predictions, the successful evaluation of a hardened CARS system, the utilization of 8000 frame/shadowgraphic movies and CH flame emissions to study the dynamic behavior of the combustor and the development of a Raman system that can collect two channels of information at rates of several hundred Hz. Figure 2 illustrates a comparison of different flow fields of the APL combustor with model predictions.

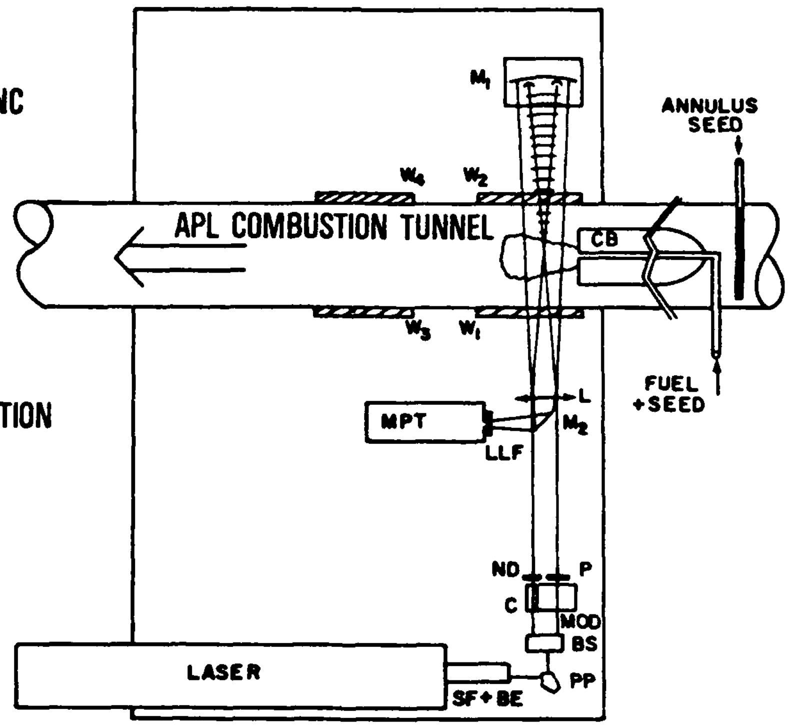
Other diagnostic programs are being sponsored by the Power Division of APL. They include investigations of the effects of turbulence on CARS, CARS spectra of water vapor measured as a function of temperature and pressure, the use of laser induced fluorescence and photoacoustic spectroscopy to measure trace species concentrations in flames. The Ramjet Division is also sponsoring diagnostic related programs to investigate biasing errors associated with LDA measurements and to develop and utilize a probe mass spectrometer system to obtain on-line measurements of species concentrations in a dump combustor.

APL COMBUSTION DIAGNOSTIC AND MODEL DEVELOPMENT PROGRAM

APPROACH

DEVELOP DIAGNOSTIC TECHNIQUES TO MEASURE VEL, TEMP AND CONC

USE MEASUREMENT RESULTS TO EVALUATE AND DEVELOP COMBUSTION MODELS



DIAGNOSTIC TECHNIQUES

CARS (TEMP, N_2, O_2, CO_2)
LDA (VEL)

RAMAN (TEMP, N_2, O_2, CO_2)

THERMOCOUPLE (TEMP)

GAS SAMPLING (CO_2, CO, THC)

OPTICAL CH EMISSIONS

HIGH SPEED CINE PICTURES

Figure 1

ILLUSTRATION OF APL EXPERIMENTAL AND P&W MODEL RESULTS

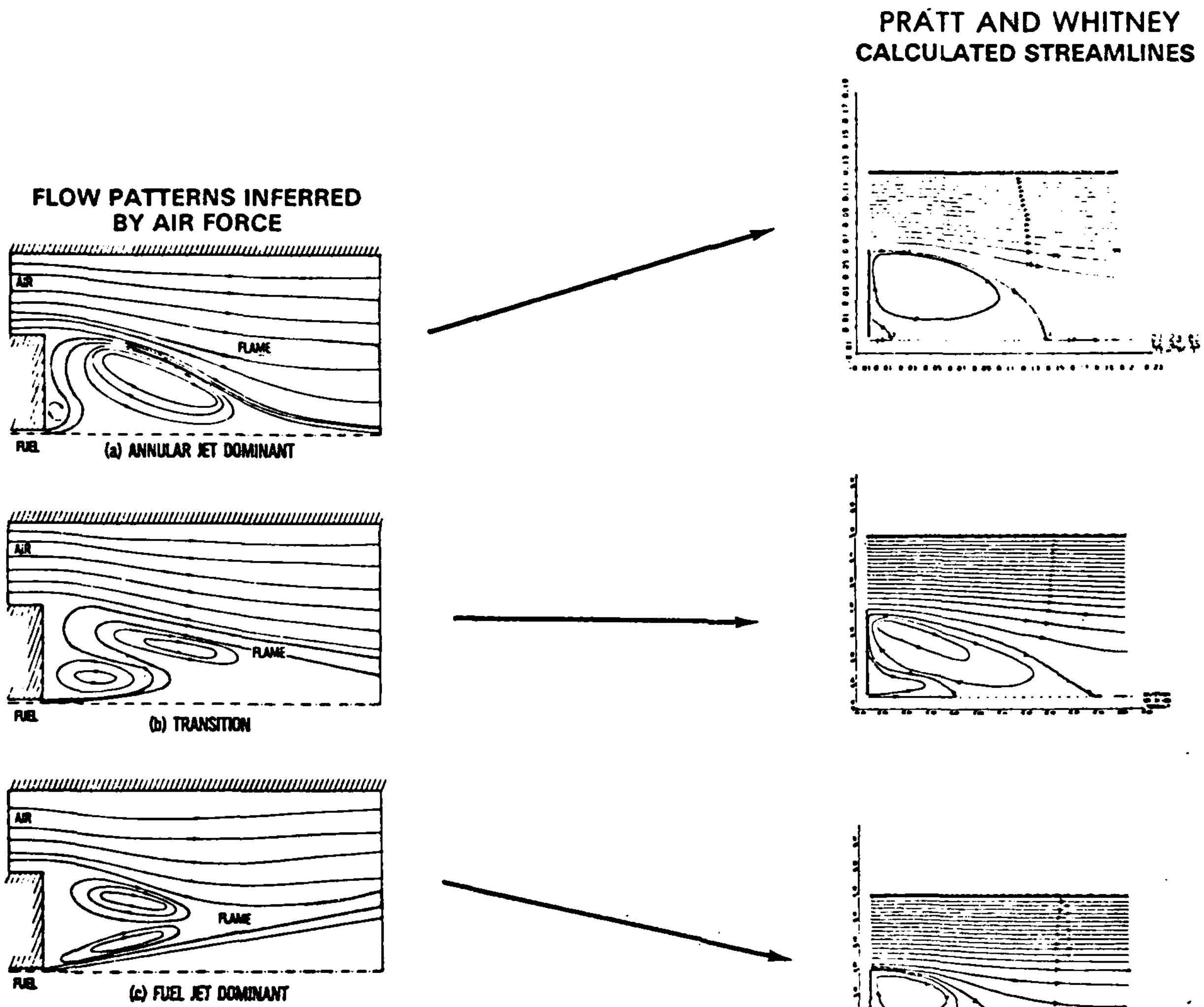


Figure 2

OVERVIEW: AFOSR RESEARCH INTERESTS IN DIAGNOSTICS OF REACTING FLOWS

Leonard H Caveny
Air Force Office of Scientific Research
Bolling AFB, Washington, DC 20332

An interdisciplinary research program is underway to provide new diagnostic techniques which are needed for the advancement and understanding of reacting flow systems, in particular air-breathing and rocket engines. The research is intended to overcome deficiencies in obtaining reliable measurements in the reacting flows of practical, hostile combustion environments. The research objectives include: to originate more sensitive, selective, precise, reliable, and rapid diagnostic methods and to measure fundamental parameters required to implement the approaches. The results will aid in reducing to practice new in-situ nondisturbing techniques for accurately characterizing reacting flows. While many of the physical principles have been anticipated, this endeavor enables combustion researchers to confront the realities of obtaining useful measurements.

A number of approaches are underway. Both tunable dye and diode laser absorption spectroscopy are being extended to include additional species, optical probes, time dependent flows and particle-laden flows. The understanding of CARS processes is being improved with respect to conversion efficiencies, line shape, and turbulence effects. With respect to optical tomography, techniques for fast scanning and recording multidetectors are being investigated along with improved convolution schemes. In-situ measurements of particle size distributions are using two-wavelength transmissometry and forward Mie scattering. Fiber optics used in conjunction with several diagnostic methods are being explored as a means of probing hostile flows. Quantitative flow visualization (species concentration, velocity and temperature) is being advanced using laser illumination of planar regions; scattered light is detected, digitized and analyzed using two-dimensional formulisms. Laser induced fluorescence spectroscopy is being extended to consider diatomic molecules in turbulent flows. Multi-coil flow field sensing, based on magnetic dipole primary induction fields, is being explored as a means of quantifying unsteady velocity components in multi-dimensional flows. This approach does not require optical access. Improved tests to validate the techniques are being devised, e. g., turbulent reacting shear layer flows (to provide the couplings between fluid dynamic and chemical processes), droplet evaporation in turbulent flows, flows with high particle loadings, and acoustically excited flows (to simulate combustion instability situations).

The presention is intended to stimulate thinking on the more challenging research goals. During the next year, opportunities exist for bold scientific approaches which can be applied to the hostile environments of high performance combustors, e. g.,
1) Ultra-high speed reaction detection of the kinetics of crystal phase change and liquid layer decomposition of energetic materials.
2) Quantitative measurements in reacting two phase flows, i.e. 2-D concentrations, temperatures, velocities of both phases, mixing parameters at shear flow interfaces.

COHERENT OPTICAL TRANSIENT SPECTROSCOPY IN FLAME

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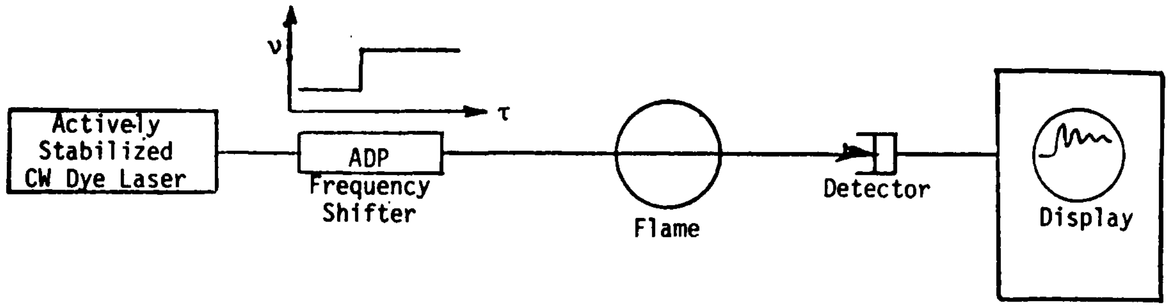
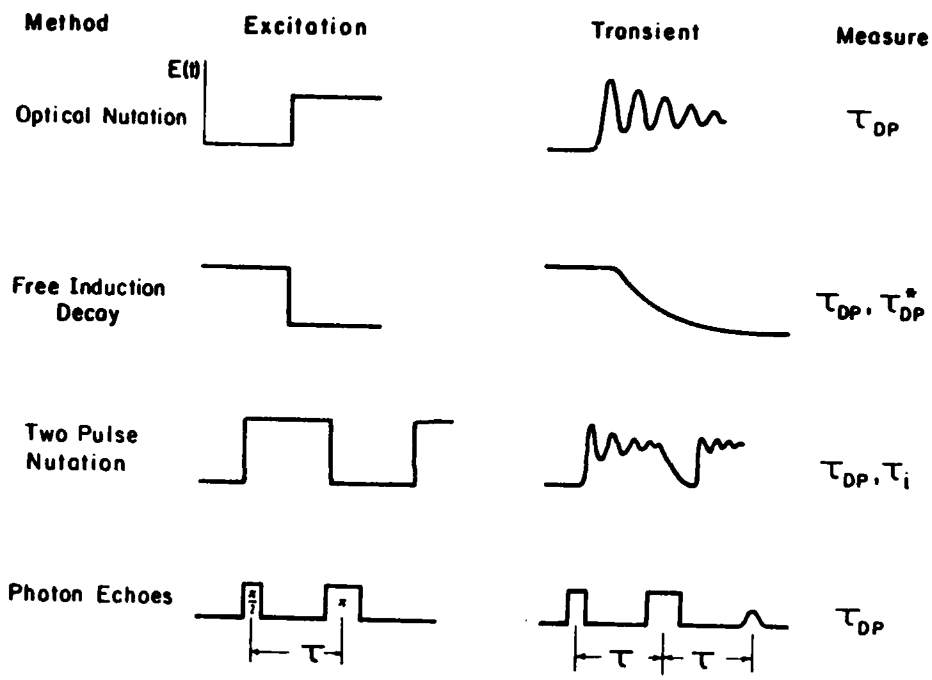
Coherent optical transient spectroscopy is a technique in which the transient response of a group of molecules to laser excitation is observed. The uniqueness of the method lies in the fact that when transient experiments are conducted on a time scale short compared to collisional relaxation times, coherent phenomena occur which enable one to directly observe the rates of a variety of collisional processes. Furthermore, the coherent phenomena can be quite strong, resulting in large signals and thus high data rates. Processes such as state-to-state energy transfer, optical dephasing and velocity redistribution can be studied.

An example experiment is shown in Figure 1. An actively stabilized CW dye laser is used as a source. By passing the beam through a traveling wave modulator to which a high voltage pulse has been applied, the frequency may be shifted up to 15 GHz within 50 psec for periods of several nanoseconds. Thus, one may shift into or out of resonance with an absorption line of interest and observe the transient behavior that results. One type of transient is optical nutation in which the laser beam is suddenly shifted into resonance with an absorption line and the absorption signal observed. The decay rate of the transient signal is the collisional dephasing rate for that transition and thus a direct measure of the line width. Also illustrated in Figure 1 are several types of excitation, the transient they produce and the quantities one can obtain.

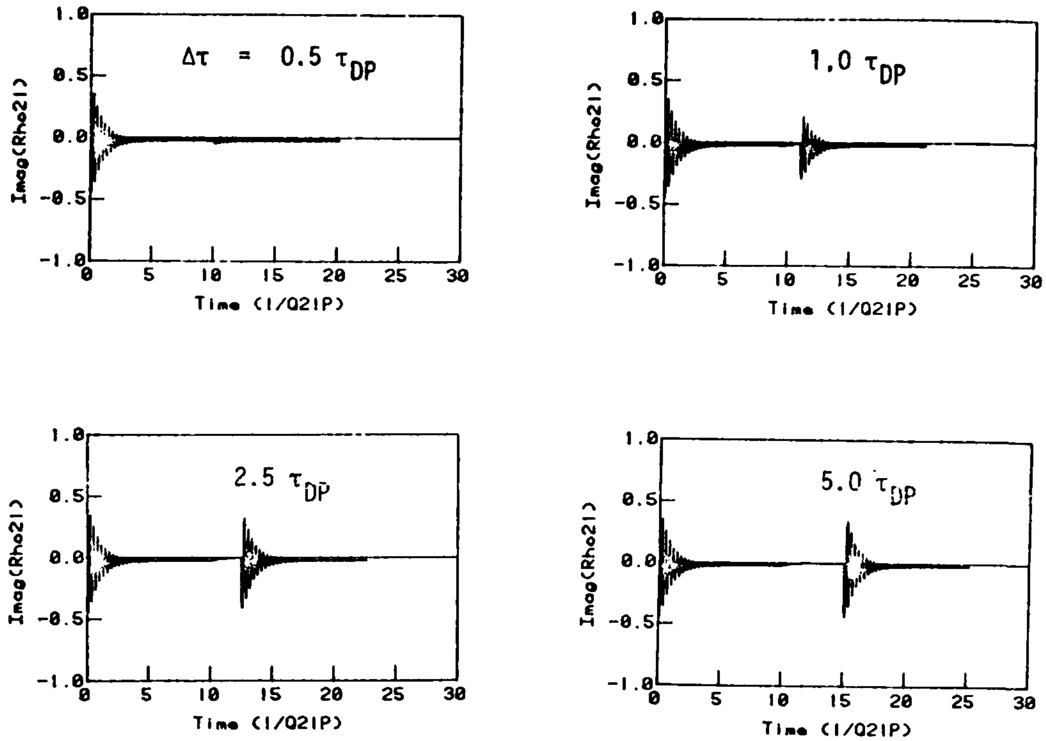
Over the last year, our work has focused on developing the theoretical capability for predicting various coherent phenomena that arise due to optical excitation of diatomic radical species of interest in flames. For example, shown in Figure 2 is the expected response to a two pulse nutation experiment in which the rotational relaxation rate for a molecule like OH or CH is determined by measuring the nutation signal strength as a function of pulse delay. Continuing the experiment to longer time delays one may also trace out chemical decay which gives a measure of state to state chemistry. By systematically varying flame composition and stoichiometry, one can study the kinetics of such processes over a wide range of in situ conditions. During the next year we will be assembling and testing the apparatus for performing coherent transient experiments in the visible region with molecules such as CH.



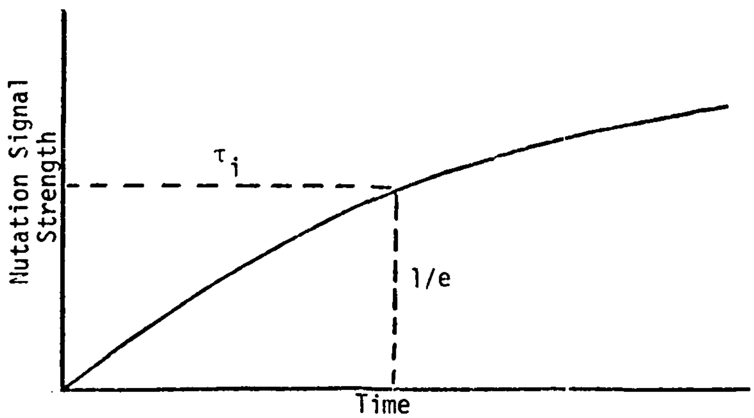


Measure	Learn	Why Important
τ_{DP} Optical Dephasing	Line Widths	Interpret Raman Spectra
τ_{vP} Doppler Dephasing	Velocity Redistribution Rates	Leads to Transport Properties
τ_i State Decay Rates	State to State Energy Transfer Rates	Interpret Fluorescence Signals
	Chemical Relaxation Rates	State to State Chemistry

Figure 1



a) Two Pulse Nutation Response



b) Signal Strength versus Time

Figure 2 Two Pulse Nutation

CHARACTERIZATION OF TURBULENT FLAMES

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In order to design improved combustion systems, advanced measurement methods have been developed that are capable of providing new laboratory data designed for the development and verification of flame models. We have been active in developing light scattering diagnostic probes that can contribute to this area of research. Thus, we have developed vibrational Raman scattering methods to determine simultaneously the temperature, density and major species gas composition (see Fig. 1), and have combined these with velocity flow field data from laser velocimetry, by conditioned sampling. Additionally, we have studied the accuracy with which the Raman technique could be applied to flame studies, and compared its attributes critically against those of alternate scattering probe methods.

The types of scientific questions that have been addressed include: What are the important turbulent combustion processes for validation of simplified flame models? What is the structure of the mixing and burning regions in these flames? Toward this end, we have studied laboratory co-flowing jet turbulent diffusion flames with fast H_2-air chemistry, and have compared our data with modeling results of R. Bilger (Univ. of Sydney). We have found that agreement with simple adiabatic models for a turbulent flame at moderate Reynolds number was possible if the effects of differential molecular diffusion of H_2 from fuel-rich zones is included. We have also estimated the average position of the flame front (from positions of maximum probability for the measured mixture fraction to be close to its stoichiometric value) and the average position of the viscous superlayer (corresponding to positions with a 50% probability that significant amounts of turbulent fluid are present). In Fig. 2 we show the axial profile of the reaction zone and the superlayer for a flame with Re=4500. We are unaware of any other measurement techniques that have been able to provide the detailed scalar data needed to analyze these problems.

To advance to the next stage of model testing and innovation, increased attention to integration of measurement techniques will be required. Thus, in addition to utilizing more fully the concommitant velocimetry data, we also will need to incorporate methods for determining answers to difficult chemical questions important to the overall turbulence/chemical kinetics issues involved in flame modeling. For example, key minor species may be determined by coupled fluorescence or coherent anti-Stokes Raman scattering probes; these data then may contribute to answering questions concerning chemical equilibria that can be important to production of nitric oxide and soot.

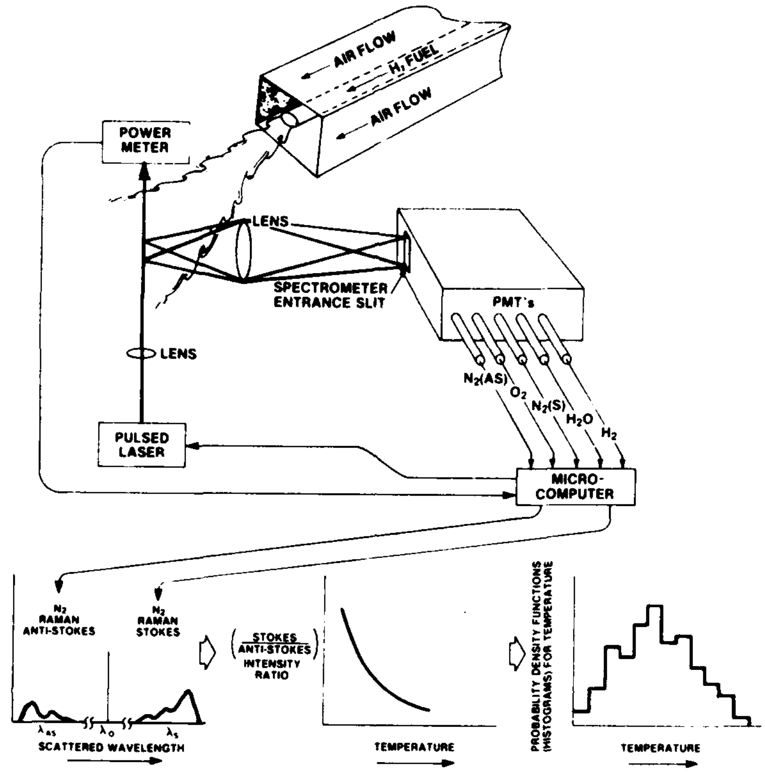

Fig. 1 This schematic shows the pulsed Raman probe, from which probability density functions (pdf's) of the state variables are obtained for the co-flowing jet diffusion flame depicted. As an example, the generation of instantaneous temperature pdf's from vibrational Raman Stokes/anti-Stokes data is indicated at the bottom of the figure. If a laser velocimetry probe is aimed at the same test volume, coordination with velocity data is obtained by triggering the Raman pulsed laser source shown here with signals derived from validated data from the velocimetry processor.

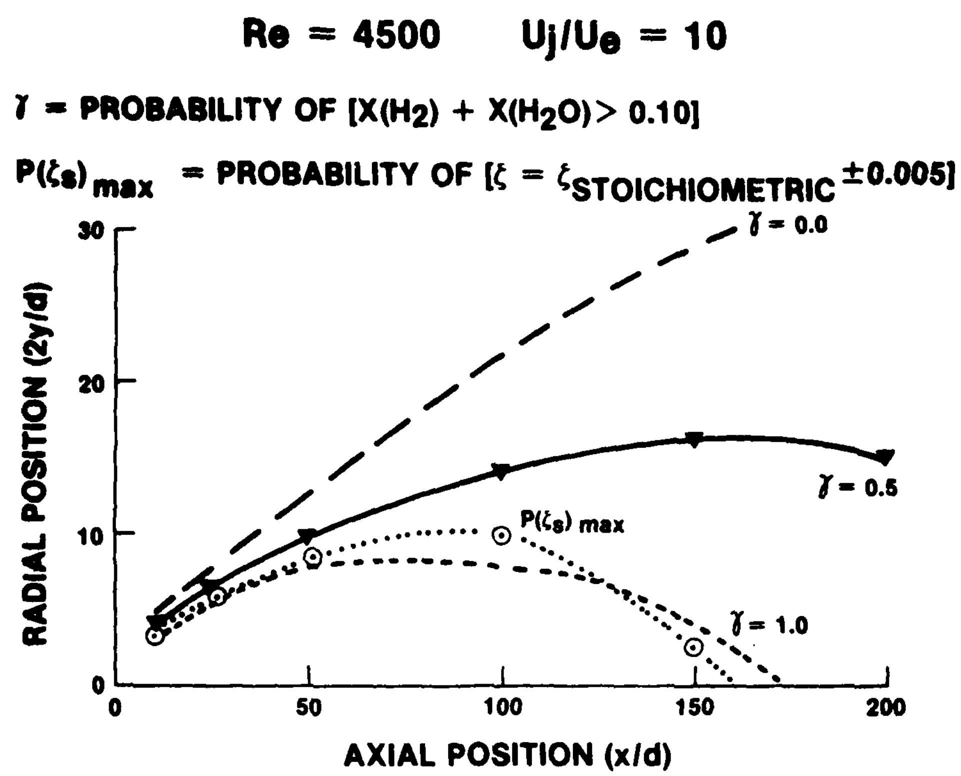

Fig. 2 Axial profile of the average positions of the reaction zone ($P(\zeta_s)_{max}$) and the superlayer (γ=0.5) for a Re=4500 H_2-air turbulent diffusion flame. Here, γ is the intermittency based upon the presence of H atoms in one form or another (i.e., turbulent fuel-related fluid), and ζ_s is the stoichiometric value of mixture fraction (a conserved scalar indicating the fractional amount of hydrogen present, relative to all species). The ratio of the average initial hydrogen jet velocity, U_j, to the initial annular air flow velocity, U_e, is 10. (Presented at ONR Project Squid Annual Meeting, Monterey, Nov. 3-4, 1981.)

NOISE THERMOMETRY IN COMBUSTION PROCESSES

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The objective of our research is to investigate the Johnson or thermal noise emitted directly from a reacting gas flow as a measure of the gas temperature. Using three different gases, we will define the temperature-gas conductivity range over which this approach is applicable; investigate the influence of boundary layers and electrical characteristics of flames on the measurements; and evaluate the response of the Johnson noise sensor to temperature and gas conductivity distributions. Our measurements will be made over a wide range of gas conditions using contact electrodes or contactless capacitively coupled sensors. By measuring the Johnson noise over a narrow bandwidth centered at megahertz frequencies, we can eventually make transient temperature measurements with microsecond response. This cannot be done for example with immersed Johnson noise thermometers because of the thermal inertia of the protective sheath.

Our approach is unique because we sense the Johnson noise of the gas directly and we simultaneously measure the impedance of the gas. As a result it is free from long term calibration drift due to sensor degradation in hot corrosive environments. The main features of our approach and the issues being addressed are illustrated in Figure 1.

To date we have installed our gas burner facility and noise measurement equipment and developed our data analysis procedures. We have fabricated a low loss impedance transformer to couple the high impedance hot gas to the 50 ohm measurement system. Extraneous sources of noise contamination have been identified and eliminated. Preliminary measurements of temperature in a natural gas flame have been made in the 2000°K range and have correlated well with thermocouple data.

The primary result of this research is to demonstrate over a practical range the correlation of temperature derived from noise power with gas flow temperature. As shown in Figure 2 this range is delimited by high gas conductivity and frequency considerations on the upper end (skin depth limit) and by low gas conductivity problems on the lower end (signal to noise limit).

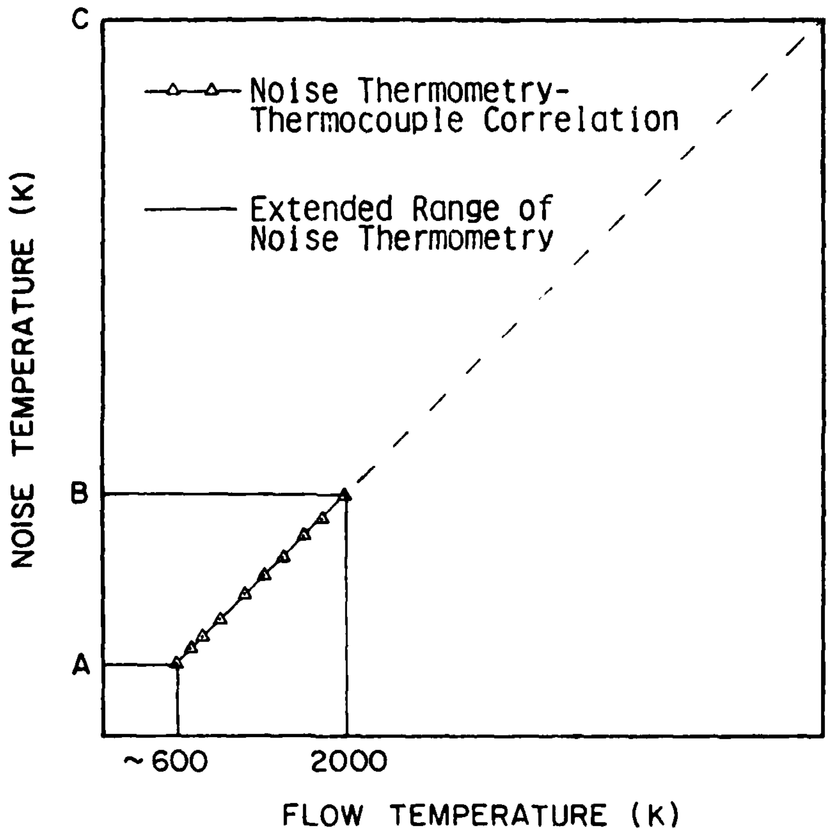
SCIENTIFIC APPROACH

- use Johnson noise emitted directly from gas flow to determine temperature
- measure source impedance after transforming for efficient power transfer to measurement system
- use contact electrodes or contactless capacitively coupled sensors

ISSUES ADDRESSED

- delimit range of temperatures and gas conductivities for three different gases
- determine influence of boundary layers and flame electrical characteristics
- evaluate response to temperature and conductivity distributions

FIGURE 1 NOISE THERMOMETRY IN COMBUSTION PROCESSES-APPROACH AND ISSUES ADDRESSED



A-Signal to Noise Limit

B-Thermocouple Survival Limit

C-Skin Depth Limit, f(w)

FIGURE 2 NOISE THERMOMETRY IN COMBUSTION PROCESSES-CORRELATION OF NOISE POWER MEASUREMENTS WITH REACTING GAS TEMPERATURE

AFRPL INTERESTS IN DIAGNOSTICS OF ROCKET MOTOR PROCESSES

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There is a compelling need for knowledge of the properties of flows produced by rocket propulsion systems. Of specific interest is knowledge of properties within combustion chambers and properties determining exhaust plume observables and contamination. A general requirement for measurements of flow properties is that the measurement technique must not perturb the flow and, generally, must be external to the flow because of the harsh environment encountered in most rocket propulsion conditions.

The needed measurements for rocket combustion serve mostly as inputs and validation data for propulsion system performance evaluation, internal models of combustion and nozzle expansion processes, and prediction models for plume observables (e.g., IR radiation, plume visibility, radar cross sections). The desired measurements include gas temperature and major species concentration, and the temperature, size, mass, composition, state and velocity of particles in flows ranging from 3,500°K - 40 atm rocket chamber conditions to the low density high altitude plumes at ambient temperature and densities.

For the case of purely gaseous flows from modern liquid propellant rockets, the currently existing spectroscopic techniques of measurement (including high and low resolution spectroscopy, resonance absorption, fluorescence, electron beam fluorescence, and laser Raman scattering) are adequate, in principle, to meet rocket propulsion system needs. Refinements in the form of instrumentation improvement, data treatment, and sensitivity and uncertainty analysis will be required on a continuous basis to meet increased accuracies required in the validation of models, and the need for more accurate fundamental data on molecular parameter, cross section, etc., is ever present.

For the case of the combined gas/particle flows from solid propellant combustion, most operational techniques for measurement of particle properties are inadequate, and techniques for measurement of gas properties in the presence of particles are largely untired. Optical techniques for particle diagnostics address only the particle size and velocity problems, and other principles must be employed to measure composition, mass, state and temperature. Gas phase methods suffer from interferences caused by background emission from particles, multiple scattering which destroys the geometrical integrity of the data, and severe attenuation and dispersion of source beams. Substantial additional work is required to address these issues.

X-RAY MEASUREMENT OF SPECIES IN TWO-PHASE FLOWS

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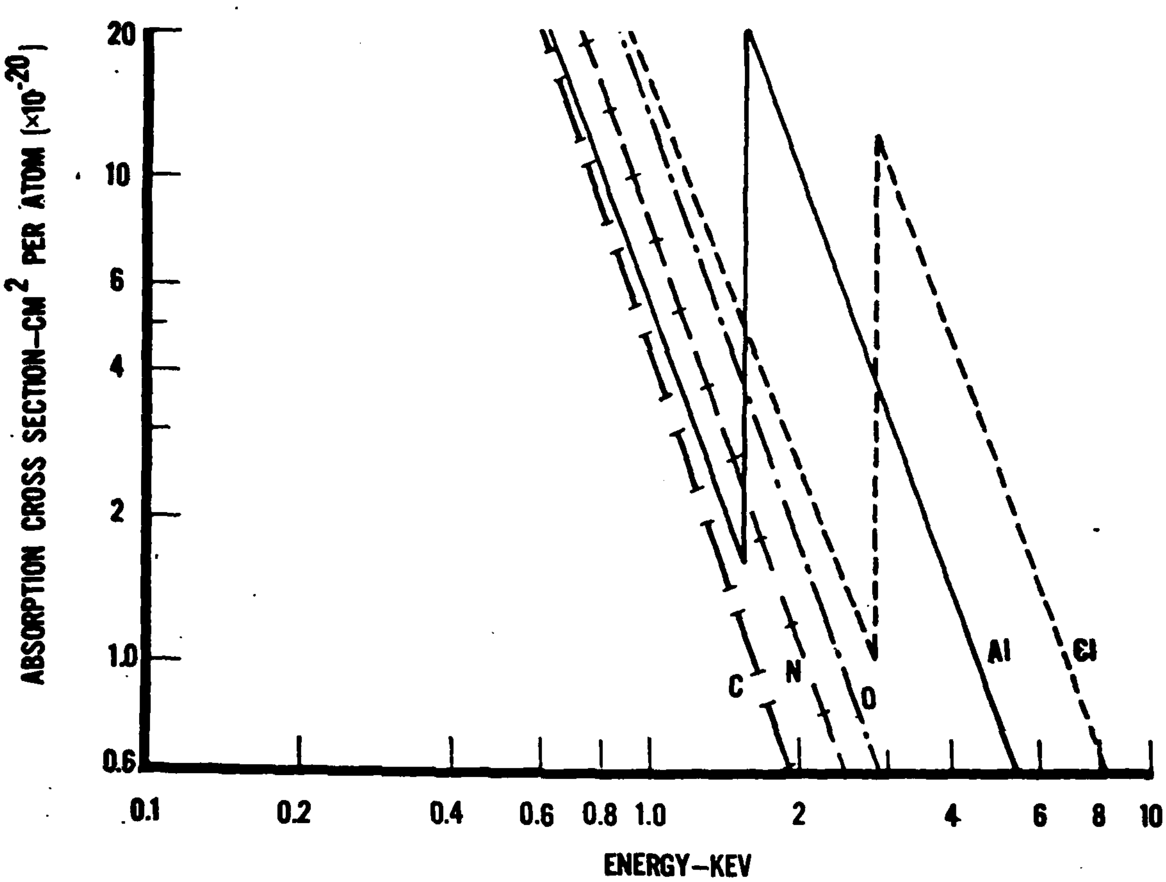
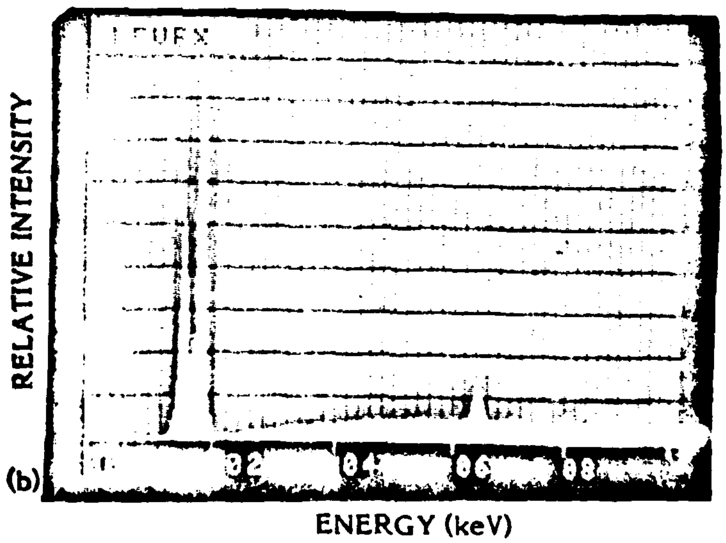
The objective of this research program is to demonstrate a diagnostic technique for measuring species concentrations in two phase flows using X-rays, and to determine the limits of applicability for the chosen method. The two basic approaches for this problem are absorption and fluorescence. From preliminary calculations, fluorescence techniques were expected to have low signal-to-noise ratios, but are straight-forward to implement. The novel approach taken in this project was to attempt an absorption technique which has the capability of determining species concentrations of elemental constituents in a mixed flow. This would be accomplished by observing differential absorption of X-rays at energies above and below an absorption edge of the element of interest. Figure l(a) depicts the absorption cross sections of the various atomic constituents found in a typical aluminized solid rocket fuel. It can be seen that aluminum and chlorine are the two contituents which are measurable by this technique. For the purposes of a demonstration, aluminum (Al) was chosen as being the more difficult measurement to achieve for technical reasons. The major technologic achievement in this program has been the fabrication of a high intensity X-ray source producing line emmission bracketing the absorbtion edge of Al. A typical output spectrum is shown in Figure l(b). The differential absorption of these two line spectra, will be sensitive to the presence of Al in the plume or two-phase flow. Figure 2 shows preliminary results of the differential absorption of these two lines through mylar without (2(a)) and with 2(b) an Aluminum deposition on the mylar. These data suggest that Al densities typical of rocket plumes can be measured with l.0% accuracy. Further measurements will be made of a two-phase flow of micron-sized aluminum oxide particles suspended in a carrier gas. Comparison of these results will be made to fluorescence measurements. The conclusion of this program will be an assessment of the feasibility of this diagnostic technique applied to rocket exhaust measurements.



(a)



(b)

Figure 1 - (a) Absorption Cross Section of Plume Constituents vs X-Ray Energy
(b) Measured Spectrum of New X-Ray Generator with Emission Lines Bracketing Aluminum Absorption Edge.

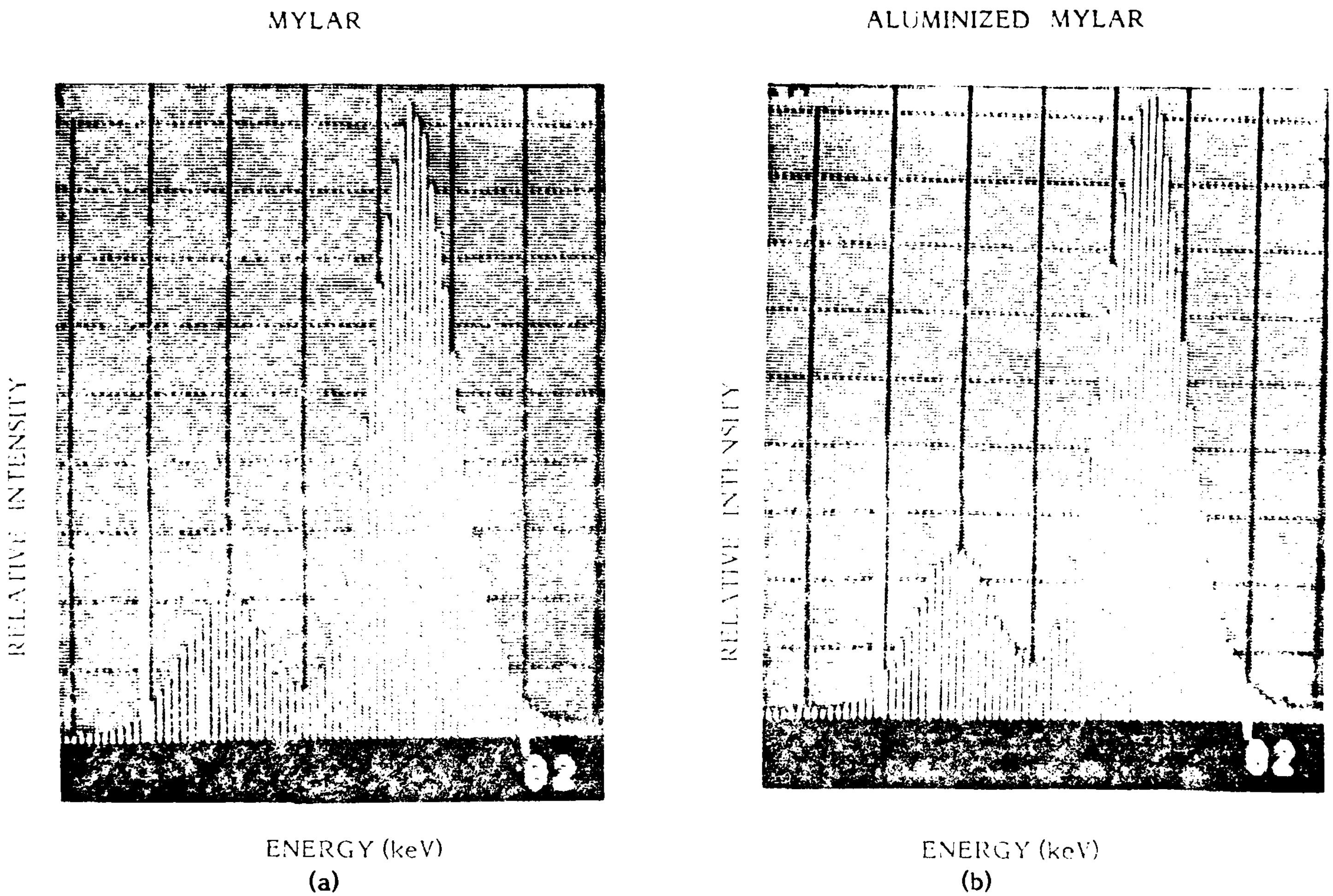


Figure 2 - Transmitted X-Ray Line Intensities Showing Differential Absorption Due to Aluminum

STUDY OF EVAPORATING FLOW USING LASER-INDUCED FLUORESCENCE

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Time scales for droplet evaporation often exceed time scales for chemical reaction or turbulent mixing in spray combustion. In such cases droplet evaporation is the physcal process which limits the overall reaction rate. An improved understanding of the development and evolution of the vapor field in droplet laden flows is an essential step toward an improved understanding of spray combustion.

Alchohol with iodine in solution is introduced in a gas flow in droplet form and as the solution evaporates laser induced fluorescence from the iodine molecules is used to study the evaporation process. Fluorescence allows point measurements to be made in a general nonsteady three-dimensional flow by using a focused laser beam to excite the fluorescing molecules and collection optics to select a particular segment of the beam path. Because evaporation can be studied as a constant pressure process, quenching of the fluorescence signal does not complicate data analysis. Iodine has an absorption band that is in near concidence with the 514.5 nm argon-ion laser wavelength and it fluoresces in the orange-red part of the spectrum. Iodine fluorescence is not fully quenched at ambient pressure and its vapor pressure is high enough at room temperature (0.3 torr) to give a significant fluorescent signal at ambient conditions. Benzyl alcohol is an example of a substance that has a vapor pressure curve that is rather close to that for iodine, and thus by matching the two vapor pressure curves and adjusting the carrier gas temperature one is able to control the ratio and rate of introduction of iodine molecules into the gas phase from the droplets.

Initially, our approach in studying evaporation is to suspend the drops in a vertically rising two-dimensional nozzle flow, where the weight of a droplet is just balanced by its drag. Because larger droplets haver larger terminal velocities, the decreasing velocity in the diffuser will cause separation of the droplets by size and allow quasi-steady suspension at different downstream stations. See figure 1. A variable pressure facility with a vertically oriented test section has been designed and a major portion of the facility has been constructed. We plan to carry out the nozzle flow work in this facility using laser induced fluorescence combined with droplet sizing and laser anemometry.

Prior to the completion of the facility, a small flowing-gas test chamber suitable for mounting on an optical table is being employed in preliminary work on developing the diagnostic technique. We have collected data on the fluorescence intensity of an iodine-nitrogen mixture for a fixed iodine partial pressure of 0.2 torr with a varying nitrogen pressure from one torr to atmospheric. See figure 2. Also we have studied the increase in fluorescence with temperature at ambient pressure. This gives basic knowledge with regard to expected signal strength for different conditions. A discovery made in related work is that for narrow band excitation, a detuning of the laser by 3 GHz causes the fluorescence signal to be far less sensitive to quenching than the corresponding line center excitation. This feature is expected to have importance in spectroscopic studies of combustion.

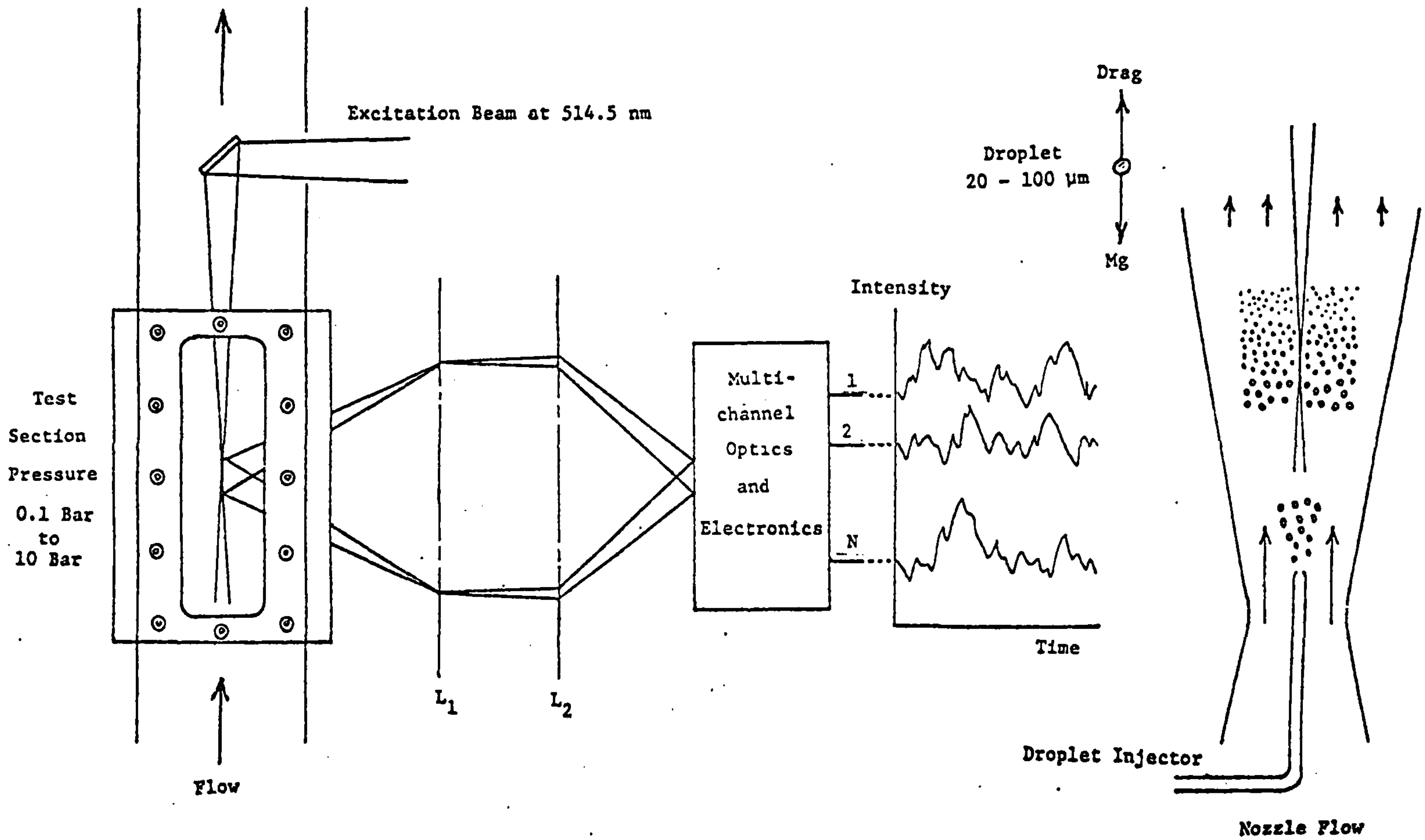

Figure 1. Multipoint Concentration Measurements About Evaporating Droplets.

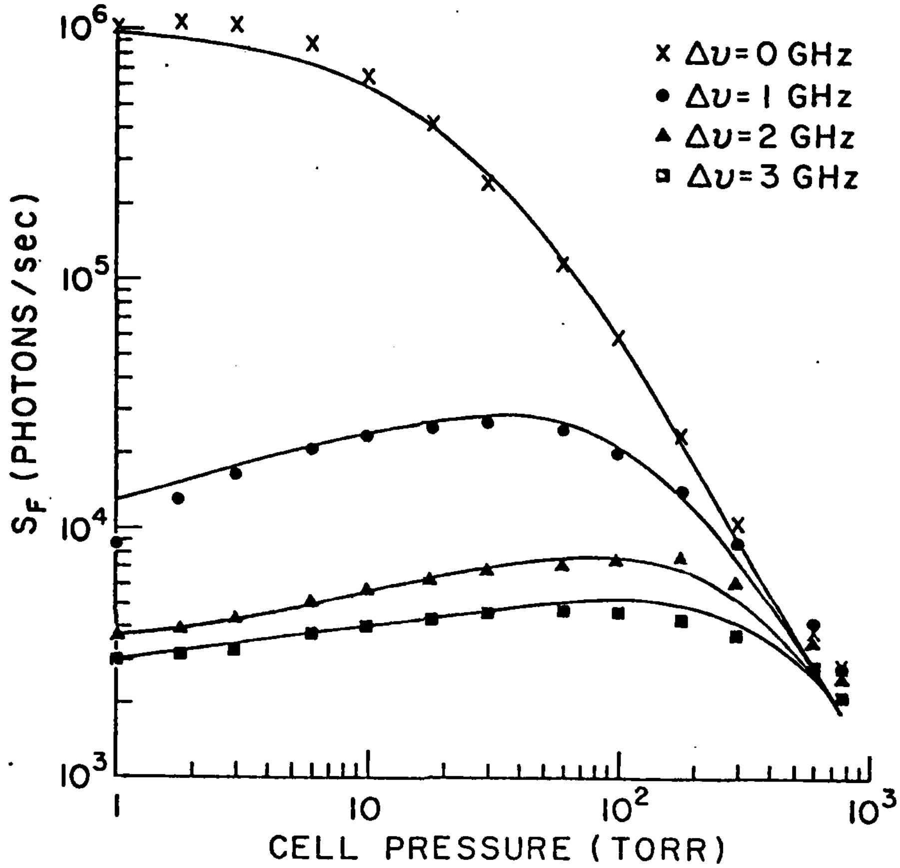

Fig. 2. Iodine fluorescence intensity as a function of pressure and laser detuning; iodine partial pressure = 0.3 torr, balance nitrogen at room temperature.

PACKAGED, FIBER-OPTIC SPECTRORADIOMETER

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ABSTRACT

This research is aimed at satisfying the need for a standard, versatile instrument for temperature measurements in flames and combustion flows at temperatures where thermocouples or other probes are inapplicable.

A compact packaged, automated spectroradiometer is being developed, based on the emission-absorption (line-reversal) technique using a resonance line of Sodium seed ($\lambda \sim 589.0$ nm). The optical system (Fig. 1a) employs fibers to transmit radiation from a standard lamp to the gas, and from the gas to a photodectector. Miniature choppers are used to generate a repetitive sequence of three signals: S_L from the lamp, S_G from the gas and S_{L+G} transmitted from the lamp through the gas. Following electronic demodulation (Fig. 1b) the three signals are used to calculate the gas temperature T_G from a simple algorithm in a minicomputer which outputs T_G with a time resolution of 1 msec. Spectral selection in the wing of the Na 589.0 nm line is achieved with a piezo-electrically tuned Fabry-Perot interferometer combined with an interference filter. A second detection channel, detuned from the resonance line, will allow corrections to be made for particle laden flows.

The whole instrument will be packaged and mounted remotely from the combustion test rig to which it is coupled by fibers which may be of considerable length.

The complete optical system has been breadboarded and tested satisfactorily. Preliminary tests of the system (excluding the electronics) have been made on a Perkin-Elmer acetylene-air burner seeded to $\sim$0.01% with NaCl. Oscilloscope traces of the detector signal as the Fabry-Perot is scanned over the wavelength range of interest are shown in Fig. 2, for various test conditions.

Further details are given in a paper to be presented at the Sixth International Symposium on Temperature: Its Measurement and Control in Science and Industry; Washington DC, March 1982.

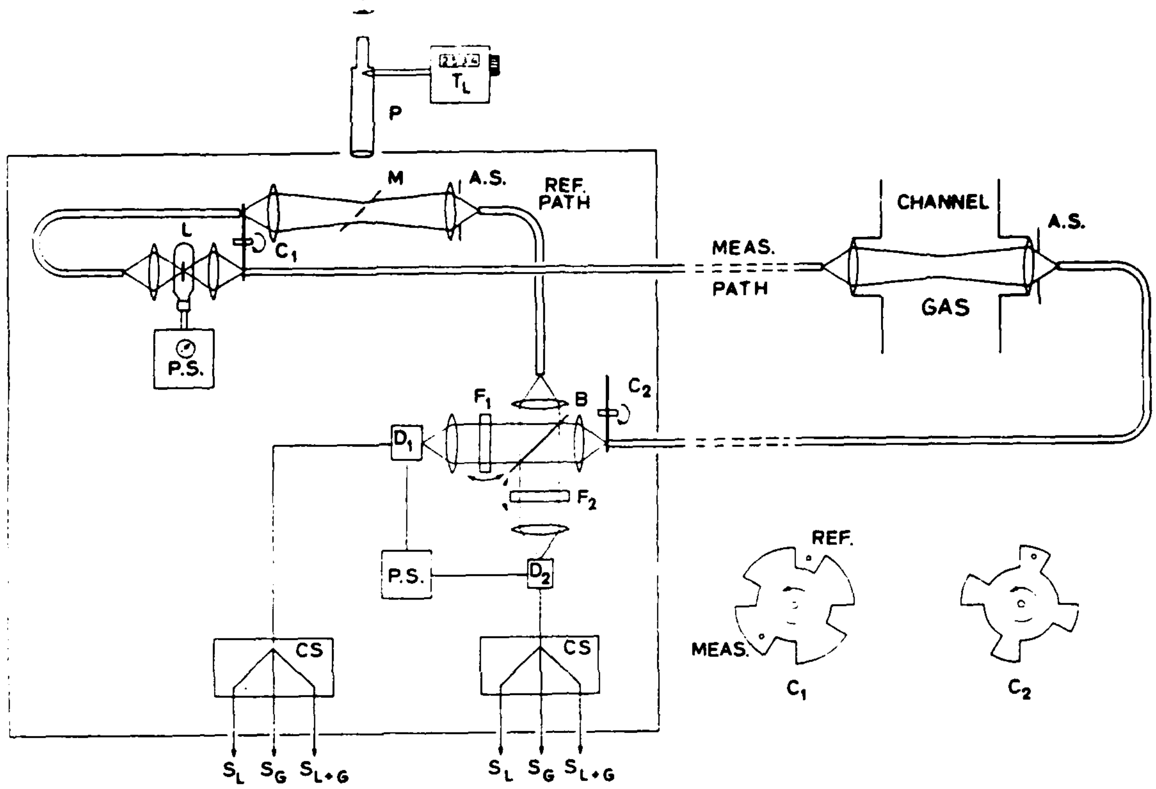

Figure 1(a). Optical Configuration: All components in boxed area are packaged and mounted remotely.

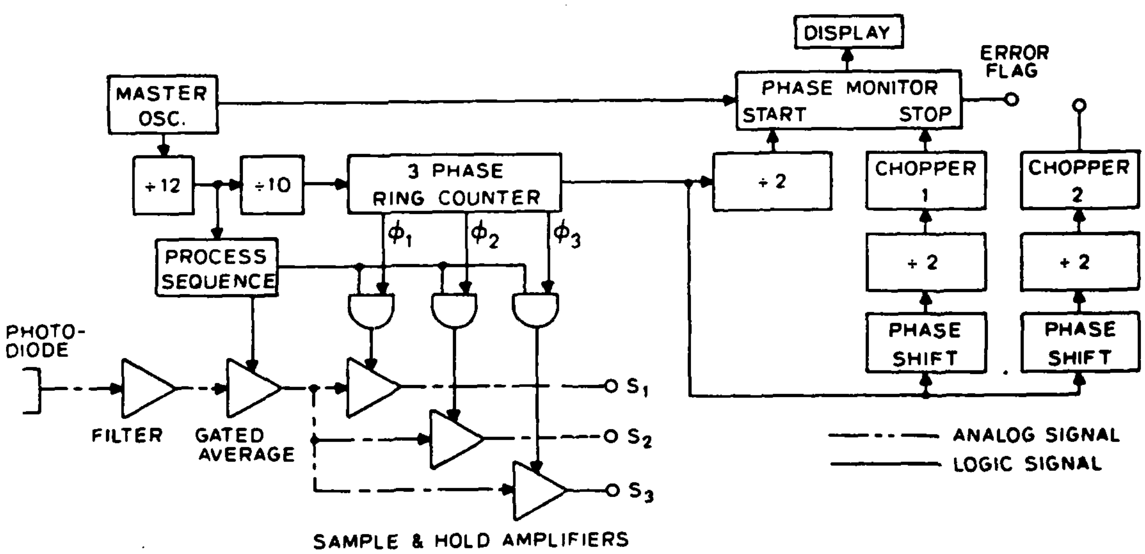

Figure 1(b). Channel Separating Electronics to Demultiplex the Chopped Signal Sequence.

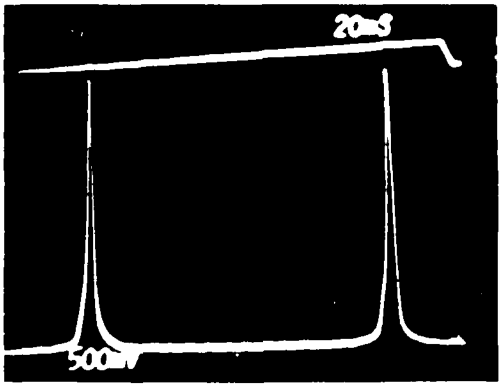

Figure 2a. Lower Trace: Fabry-Perot response to He-Ne laser showing two adjacent modes 18 nm apart. Upper Trace: Ramp voltage applied to scan Fabry-Perot.

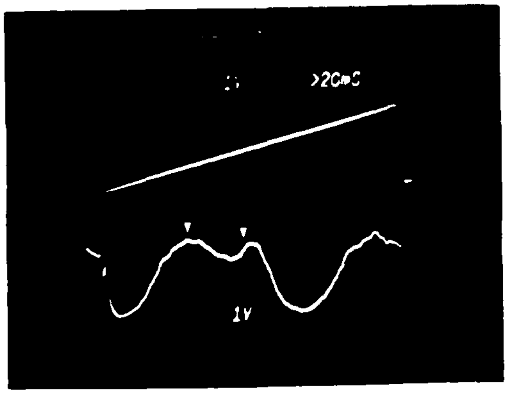

Figure 2b. Lower Trace: Response of Fabry-Perot-filter combination to tungsten lamp radiation. Markers show positions of Na resonance lines at [illegible], [illegible] nm.

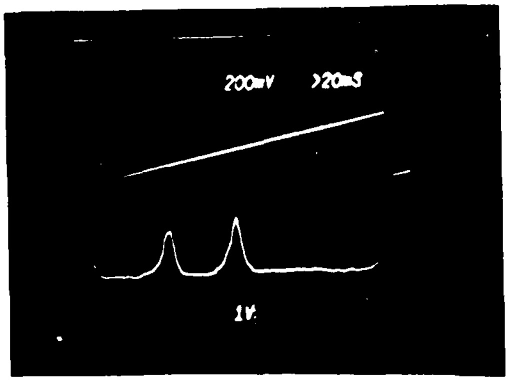

Figure 2c. Lower Trace: Response of Fabry-Perot-filter combination to Na resonance lines from acetylene air burner.

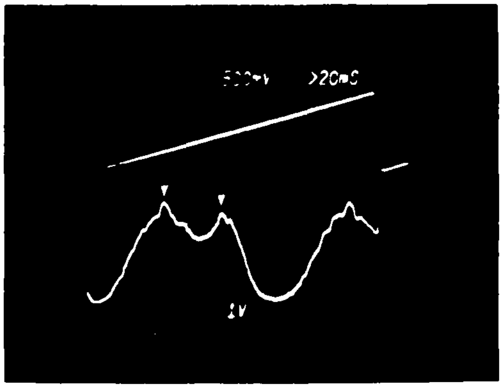

Figure 2d. Lower Trace: Response of Fabry-Perot-filter combination to lamp transilluminating flame.
T_L = [illegible] K T_G = 2180 K.

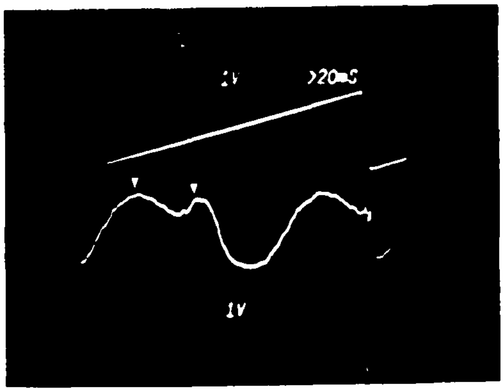

Figure 2e. Lower Trace: As above but with $T_L = T_G = 2180$ K.

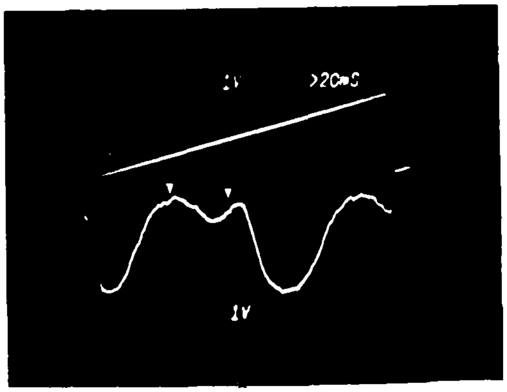

Figure 2f. Lower Trace: As Above but with T_L = [illegible] K.

PARTICLE SIZE DISTRIBUTION AND VELOCITY VIA NUMERICAL HOLOGRAPHIC RECONSTRUCTION

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Hassan Mostafavi

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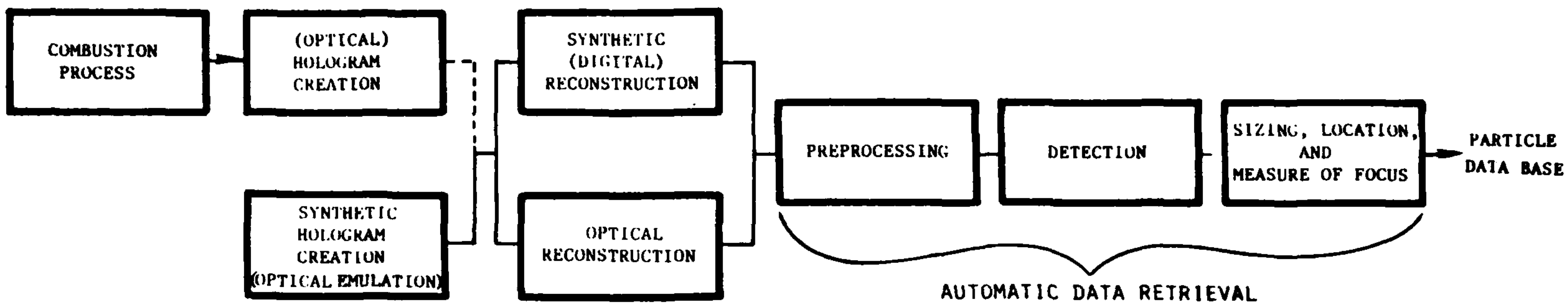
Los Gatos, California

Holographic techniques are useful for the study of combustion processes; this has led, for example, to the development of hardware such as the holocamera at the Air Force Rocket Propulsion Laboratory. The retrieval of data from the hologram, however, requires an appropriate level of automation if the manpower requirements are to be made acceptable. There are a number of theoretical issues associated with the feasibility, extent, and manner of automation throughout the recording, reconstruction, and data retrieval process. An important question here relates to the determination of the theoretical limits on the particle size discrimination for various experimental configurations. The determination of these theoretical limits also requires careful considerations related to the particle shapes that are expected (e.g. roughly spherical or highly irregular), since this influences the filtering and/or pattern recognition techniques that are appropriate.

The systematic approach for addressing these questions will include the possibility of digitizing the hologram and reconstructing the image by digital rather than by optical means. This is indicated in Figure 2. For the purposes of the study, a synthetic hologram will be used. Lens aberrations, speckle, and other noise effects will be simulated. Following the reconstruction process, image processing techniques appropriate for automatic data retrieval from the reconstructed image will be applied. This will include a preprocessing stage, a detection stage (matched filter), and sizing, localization, and focusing of the particles.

The approach is unusual in that it may be possible to establish that all processing after the initial hologram recording can be carried on the computer automatically, cost effectively and with acceptable resolution. The expected results are indicated in Figure 2.

This approach has only recently become viable as a result of rapid advances in digital computing power.

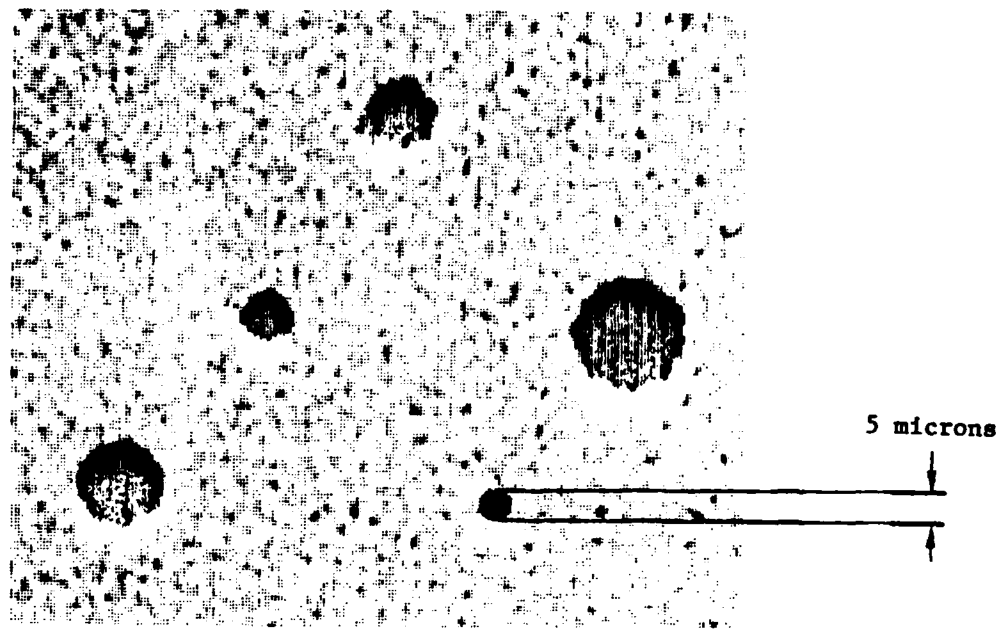


APPROACH:

- Create synthetic hologram, adding lens aberrations and noise/speckle effects.
- Develop and implement algorithms for digitally reconstructing hologram, including noise compensation.
- Explore algorithm performance, sensitivity.
- Analyze requirements for automatic data retrieval.
- Establish quantitative theoretical limits on particle size discrimination for various alternative processing and data retrieval steps.

Figure 1 - SCIENTIFIC APPROACH

SIMULATED IMAGE OF PARTICLES
AND SPECKLE NOISE



RESULTS:

- Digital Procedures for Hologram Reconstruction currently competitive with optical methods.
- Automatic Data Retrieval using digital methods appropriate .
- Particle Resolution on order of 5 microns achievable.

Figure 2 - EXPECTED RESULTS

DETERMINATION OF LIQUID DROPLET EVAPORATION RATES IN A SPRAY BY INELASTIC LIGHT SCATTERING

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Combustors and their chemical by-products are sensitive to the size distribution of the fuel droplets. The evaporation rate of a single droplet within a spray depends on the heat flux directed toward it and on its vapor environment. Both of these quantities depend on the proximity of neighboring particles and also on the collective evaporation and combustion properties of all the droplets.

The objective of this new program is to develop a new quantitative optical technique for determining the evaporation rate of droplets in a spray. The standard _in-situ_ optical diagnostic technique infers the droplet radius from the angular pattern of the elastically scattered radiation $I_{ela}(\theta,\lambda_i)$ at wavelength λ_i. We have recently developed a new technique for size determination of spheres and cylinders in which the elastically scattered intensity $I_{ela}(\theta_1,\lambda)$ collected at a fixed angle θ_1 is analyzed spectrally. Sharp peaks occur in $I_{ela}(\theta_1,\lambda)$ as a result of morphology dependent resonances, which correspond to the natural frequencies of the micro-object.[1] Physically, these resonances result from internal electromagnetic waves near the perimeter which are internally reflected at the interface and are in phase on successive trips around the micro-object.[2] Another related approach to size determination consists of measuring the spectral distribution of the inelastically scattered intensity $I_{inela}(\theta_1,\lambda)$ collected at a fixed angle θ_1. The fluorescent molecules embedded within or coated on the surface of these micro-objects can act as a probe of the internal or near-field intensities.[3] When the fluorescence wavelength is on resonance, more of its near-field intensity will be coupled out as far-field radiation by the micro-object.[3] Figure 1 shows the $I_{inela}(\theta_1,\lambda)$ from a single dye-containing polystyrene sphere as it floats in and out of the laser focal volume.[4]

We propose to measure the evaporation rate of a small number of droplets within a spray. A few droplets will be tagged with fluorescent dye while the majority will be untagged. Upon traversing the laser illuminated volume, $I_{inela}(\theta_1,\lambda)$ from the few tagged droplets at different locations will be imaged onto the SELFOC circle-line converter (see Fig. 2). The size of these few tagged droplets at time t_1 can be determined from $I_{inela}(\theta_1,\lambda)$-position results. To determine the droplet size change due to evaporation, a new set of $I_{inela}(\theta_1,\lambda)$-position data will be measured at $t_1 + \Delta t$. The size of the untagged droplets will be measured with the same experimental system except that a flashlamp will provide the broadband illumination. The peaks in the $I_{ela}(\theta_1,\lambda)$ from droplets at many different locations will provide the radius information on the untagged droplets which are near the tagged droplets.

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2. J.F. Owen, R.K. Chang, and P.W. Barber, Opt. Lett. _6_, 540 (1981).
3. J.F. Owen, P.W. Barber, P.B. Dorain, and R.K. Chang, Phys. Rev. Lett. _47_, 1075 (1981).
4. R.E. Benner, P.W. Barber, J.F. Owen, and R.K. Chang, Phys. Rev. Lett. _44_, 475 (1980).

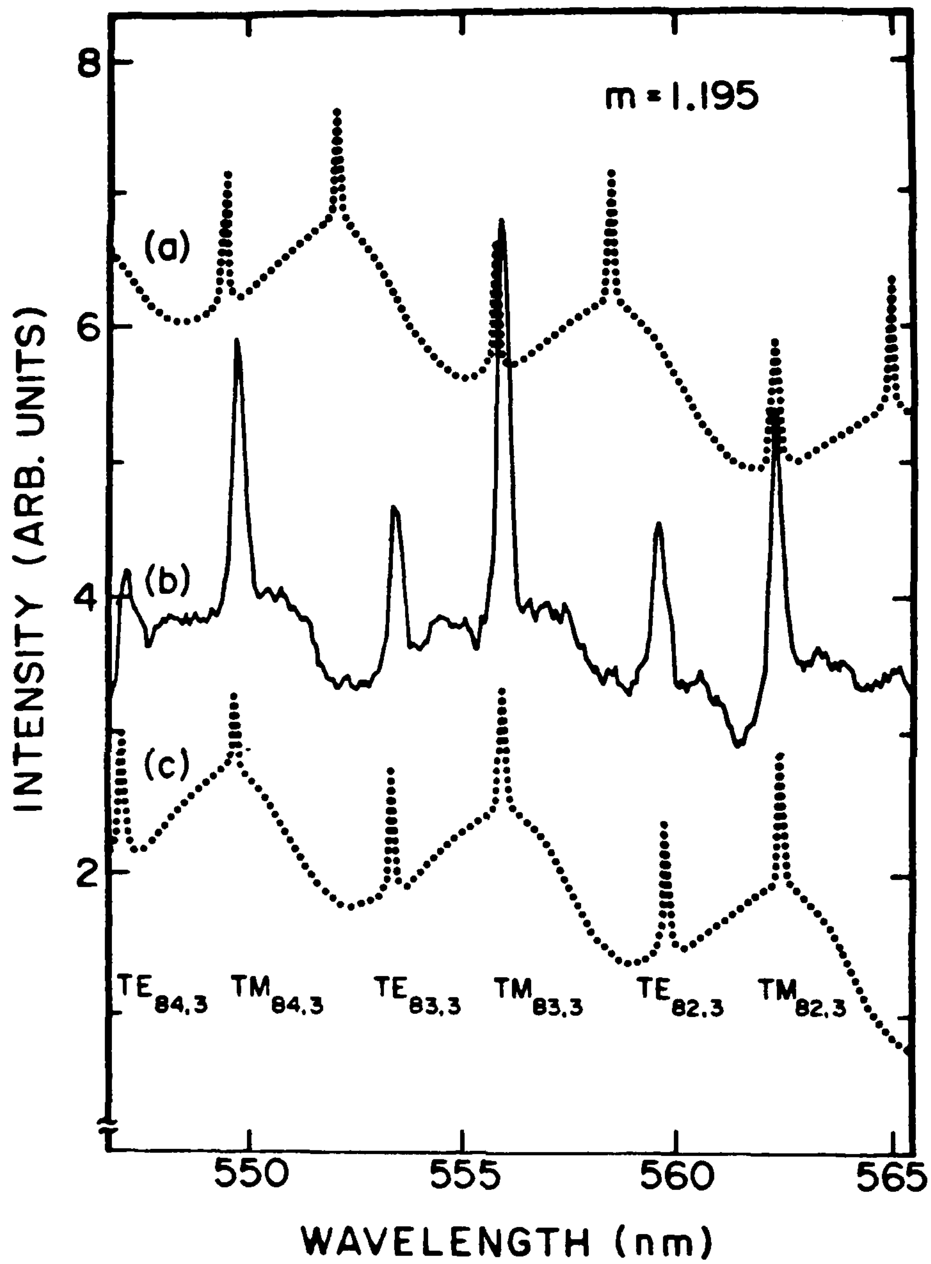


Figure 1. Fluorescence spectra from a single polystyrene sphere in water. In this wavelength range, the fluorescence spectra from a bulk medium is smooth. Curve a, theoretical result for a 9.92 μm sphere; curve b, the experimental result; and curve c, the theoretical result for a 9.99 μm sphere. The resonant peaks in curves b and c are identified by their mode numbers (84, 83, and 82) and mode orders (3).

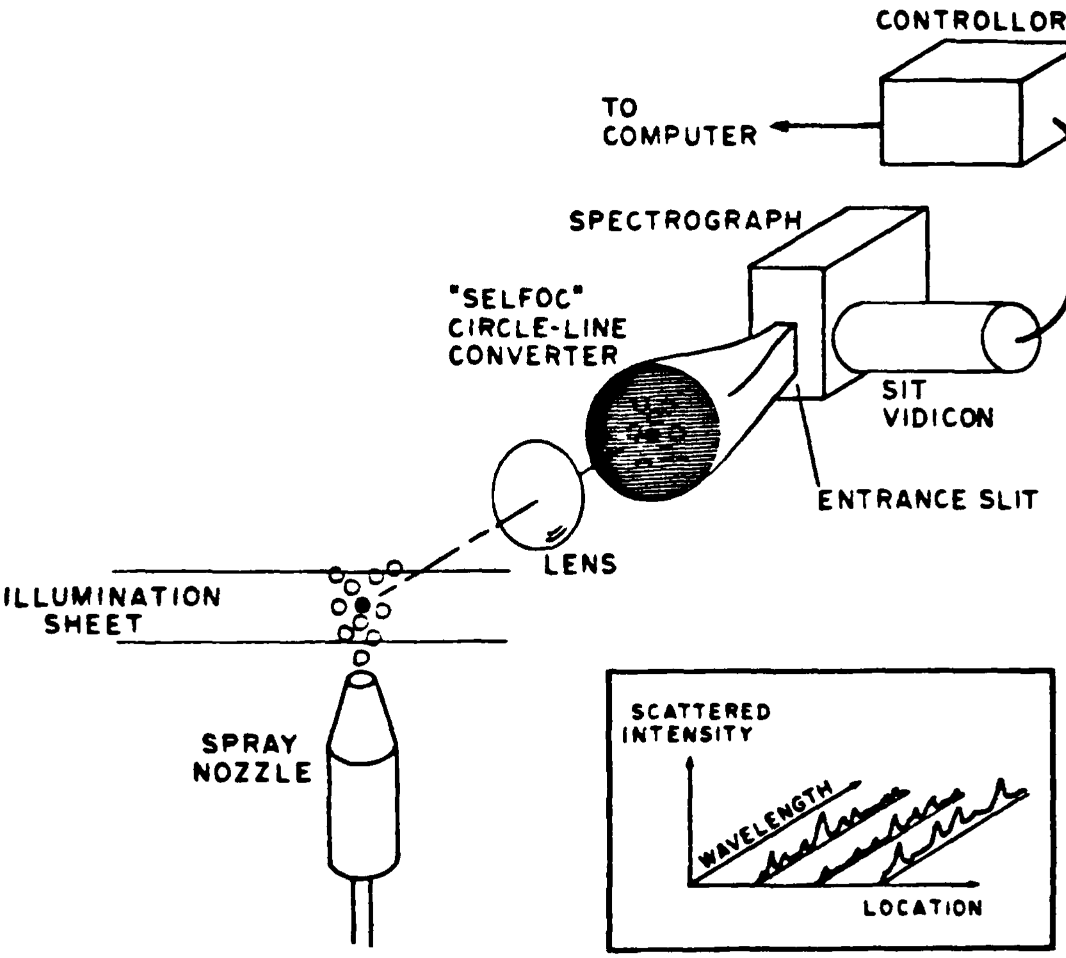


Figure 2. Schematic diagram of the configuration for measuring the fluorescent spectra and elastic scattering from spatially resolved droplets within a spray. The inset shows the form of the results that will be obtained from the computer-controlled TV camera (SIT vidicon). For the few tagged droplets, the sharp peaks in the broad fluorescence spectra will provide the size information. For the majority of untagged droplets, the sharp peaks in the broad elastically scattered spectra will provide the size information.

MAGNETIC FIELD COUPLED VELOCIMETERS

Dr. Carl Spight

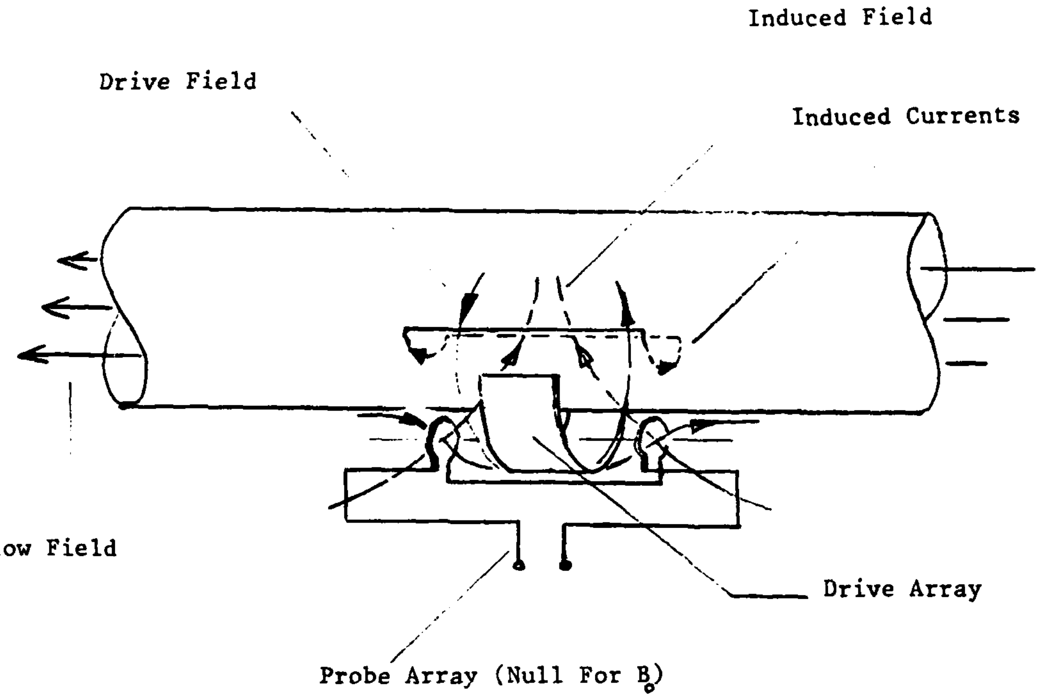
AMAF Industries, Inc.
Columbia, Maryland

A program of theoretical analysis, computer simulation, and experimental verification is underway which will demonstrate the feasibility of a totally non-intrusive flow-field diagnostic for weakly turbulent, high temperature chemically reacting flows. The effort will result in viable designs for AC magnetic field-coupled velocimeters capable of accurately measuring the mean and the turbulent velocity structure of flow-fields typical of rocket combustion chambers and exhaust nozzles.

<u>Approach</u> (See Fig. 1)

A drive dipole magnetic field array produces a harmonically varying, spatially localized and controlled field which penetrates the flow-field to produce eddy and Lorentz-field currents. These currents are determined in part by flow boundary conditions. The fields produced by the currents (with distinguishable geometric structure) is picked up by a probe array designed (by lead-field theoretic techniques) to differentiate eddy currents from motional currents. The probe array is constructed to give null signals when coupling directly to the drive array. The spatial structure in the drive field and the probe field sensitivity provides the basis for determining the velocity structure of the flow-field. Since the coupling to the flow is purely inductively the diagnostic approach being developed here is uniquely non-intrusive.

Fig.1



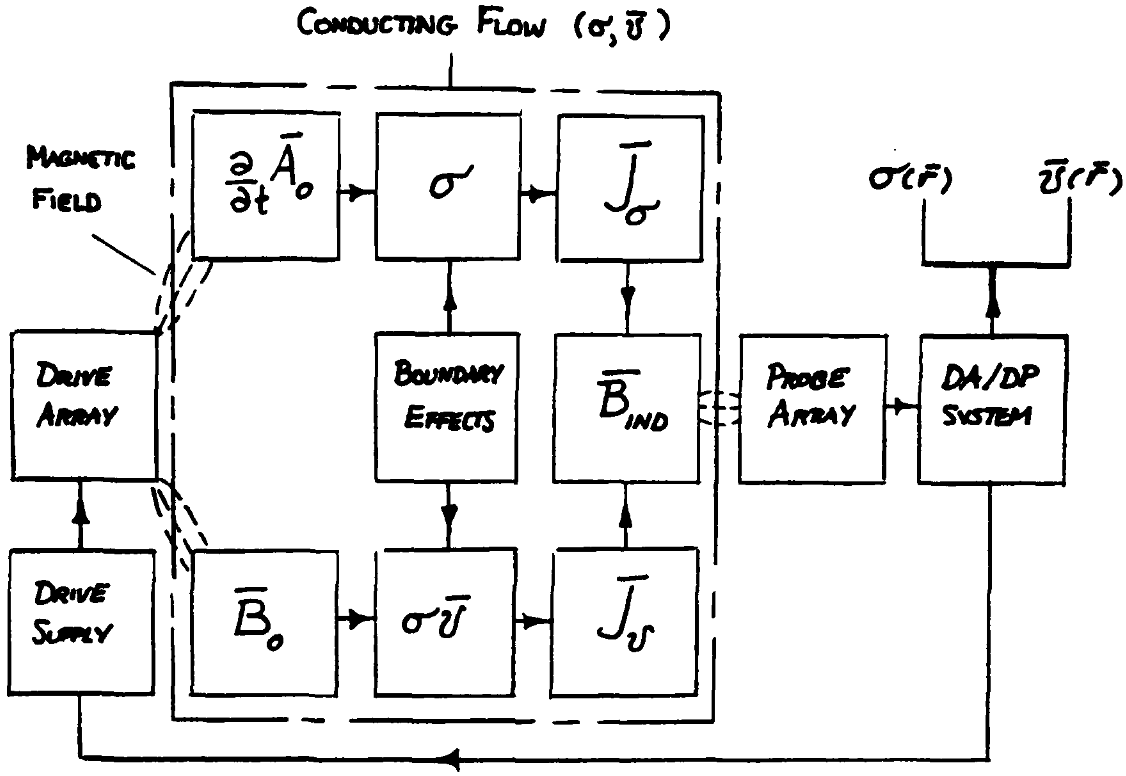
SCIENTIFIC APPROACH

- CHEMICALLY REACTING (CONDUCTING) FLOW-FIELD IS EXPOSED TO AC MAGNETIC FIELD.
- STRUCTURE OF INDUCED CURRENTS MEASURED BY A PROBE ARRAY ARE INVERTED BY LEAD-FIELD TECHNIQUES TO YIELD VELOCITY STRUCTURE.

ISSUES BEING ADDRESSED

- NO DIRECT CONTACT WITH FLOW (NON-INTRUSIVE).
- MEASUREMENT OF MEAN VECTOR FLOW VELOCITY FIELD, $\langle \underline{v}(\underline{r}) \rangle$ AND TURBULENT VECTOR FLOW-FIELD, $\Delta\underline{v}(\underline{r})$ (WITH DESIGN ASSUMPTION OF $|\Delta v/v<1$).

Fig. 2



BASIS: $\nabla \times \bar{B}_{IN} = \mu_0 \sigma \left(-\frac{\partial}{\partial t}\bar{A}_0 + \bar{v} \times \bar{B}_0 - \nabla \psi_{BOUNDARY}\right)$

Accomplishments.

- Theoretical analysis well elaborated with all important effects
- Computer code implementing theory developed for slab and cylindrical flow models
- Electrolytic chamber test of theory validated basic approach including treatment of boundary effects
- The data acquisition/data processor system (DA/DP) has been designed. Its construction is underway.

MULTIANGULAR SCANNING ABSORPTION TECHNIQUES FOR THREE DIMENSIONAL COMBUSTION DIAGNOSTICS

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The George Washington University
Washington, D.C. 20052

Objective

Combustion in flames is a process largely controlled by the access of oxydizer molecules to the fuel. Thus, pyrolysis and oxygenation are controlled by fluid dynamic mixing rates, laminar, transitional and turbulent. Recent high speed shadographs (≈ 1 KHz) have shown qualitatively that the interface of initially orderly fuel-oxydizer streams undergoes an amplification of surface ripples into coherent structures which grow, coalesce and eventually breakup into a fully turbulent flow. Since chemical kinetics are orders of magnitude faster than diffusion processes, flame combustion begins to occur at these interfaces and is therefore conditioned by coherent structure history. Thus, it is desirable to develop a method which could monitor quantitatively the time history of three dimensional flame structures with repetition rates in the KHz range (uniqueness).

Method

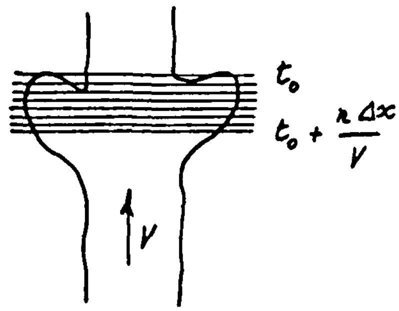
As shown in Fig. 1, a set of m parallel absorption scans taken from n different angles can be treated mathematically to yield a mxn map of concentrations. This tomographic method, which established itself in a wide medical market (CAT Scanners), is being converted under this grant from a steady state, 2-dimensional, X-ray absorption device, to a 3-*dimensional*, optical diagnostics, operating in the KHz range. Thus, 3-dimensional distributions of flame elements (soot, CO, OH,...) can be documented in real time, either in the slicing mode by a linear sensor array or in the 2-dimensional instantaneous mode by a square array (Fig. 1).

Progress to Date

In the current phase of activity, a laser beam has been transformed into a sheet of light (slicing mode, see also Fig. 2), and made to converge on a 126-element array, with electronics suitable for repeatable 1.5 KHz scanning and data processing. Available memory modules (4K) allow for 34 successive slicings of a passing target within 20 milli-seconds. In this manner, a detailed projection of three-dimensional flow field concentrations is available. An axisymmetrical flow (tobacco smoke rings) has been measured and a tomographic procedure was applied to these data. Better ranges of absorption are being considered and multiangular experiments (non-symmetrical cases) will follow.

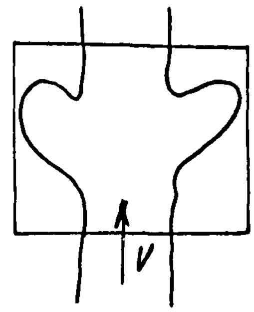
The construction of a portable tomographic unit operating in the instantaneous 2-D mode is also in progress at GWU. It couples a CAMAC digitizer with a MINC minicomputer. The source and sensor part of the experiment have been completed. Data processing and flow controls are underway.

A theoretical review of flow instabilities is in progress. It is expected that it will reveal the range of flow conditions where the unique potential of high speed tomography could be best used.



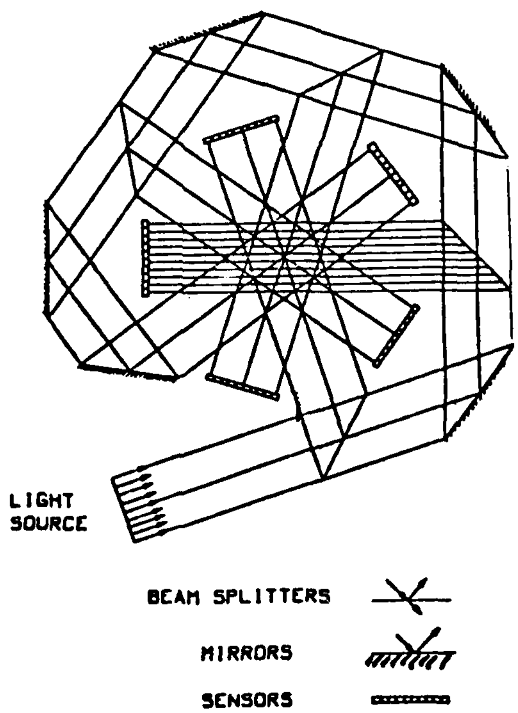
<u>Linear Array Slicing</u>

Relative motion of the fixed laser sheet with respect to the moving flow structure



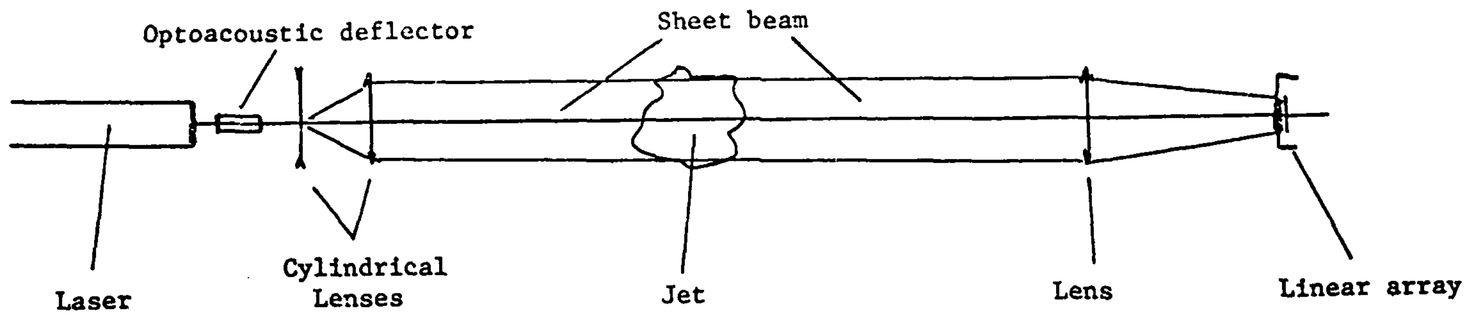
<u>Rectangular Array Matrix</u>

Instantaneous (50 μsec) data collection for the whole structure

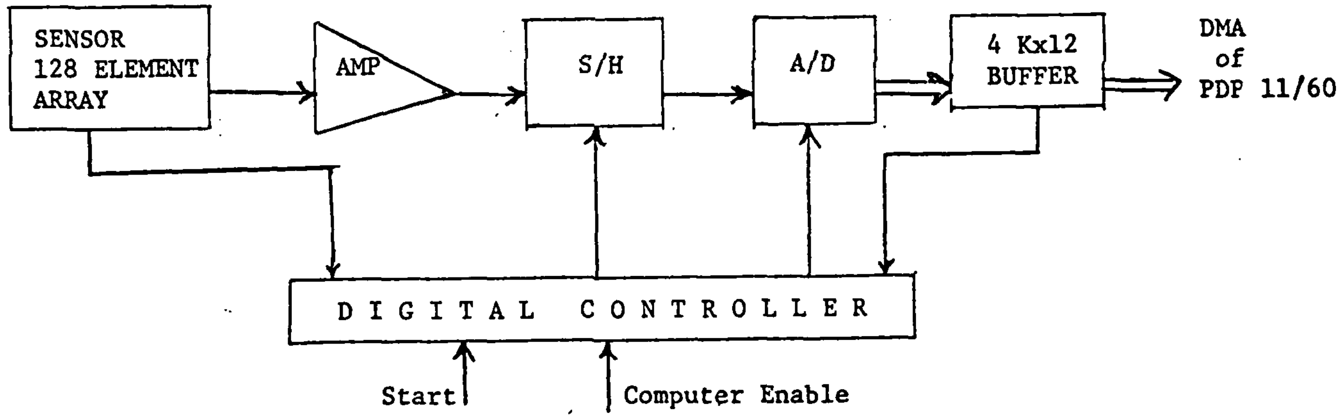


Real time multiangular scanning (optical tomography).

FIGURE I



a) Optical layout



b) Data processing

Fig. 2 - Real time tomography of an axisymmetrical jet

COMPUTED ABSORPTION TOMOGRAPHY

Robert L. Byer
Applied Physics Dept.,
Stanford University

We have designed and are constructing a cw laser fan beam geometry laser tomography imaging system. The schematic of the measurement approach is shown in Fig. 1. Tomography promises to provide a two dimensional image of species concentration in a plane with both cw and pulsed laser sources.

During the past year we have investigated laser tomography in detail. Our studies of tomography have been by computer modeling. The results are to be published as the lead article in the April issue of Applied Optics.[1] Figure 2 illustrates a tomographic model reconstruction image of a multicolored pattern on a 60 x 60 grid. We can now carry out tomographic reconstructions for both fan beam and axial beam geometry tomography and display the images on a high resolution color monitor.

Work is in progress toward completing the optical tomography system and the high speed data link to the computer. Our first goal is to demonstrate and verify the quantitative measurement capability of tomography in a subsonic mixed gas flow system.

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1. D.C. Wolfe and R.L. Byer, "Model Studies of Laser Absorption Computed Tomography for Remote Air Pollution Measurements", to be published in Applied Optics, April 1982.

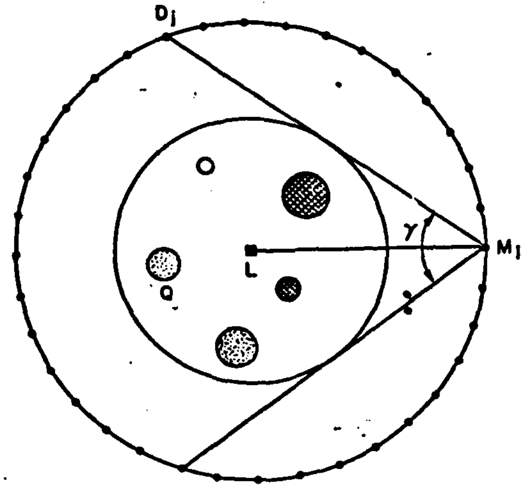
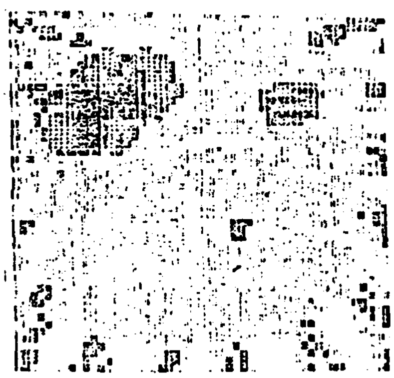
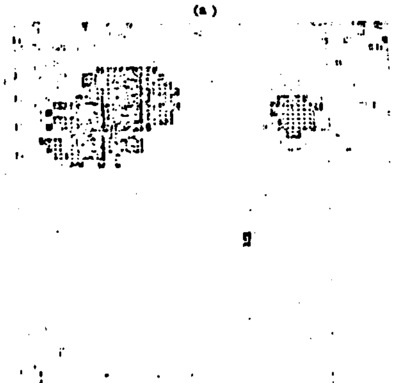


FIG. 1--Virtual source laser computer tomography. M_i is the ith virtual source. D_j is the jth detector of the ith projection fan. L is the laser source. The outer circle defines the locations of the virtual sources and detectors while the inner circle defines the area being imaged. The cross-hatched areas represent pollution clouds



(a)



(b)

Fig. 2--Multicloud reconstruction test.
a) 100 detectors/fan and 20 fans,
b) 100 detectors/fan and 100 fans.

QUANTITATIVE FLOW VISUALIZATION

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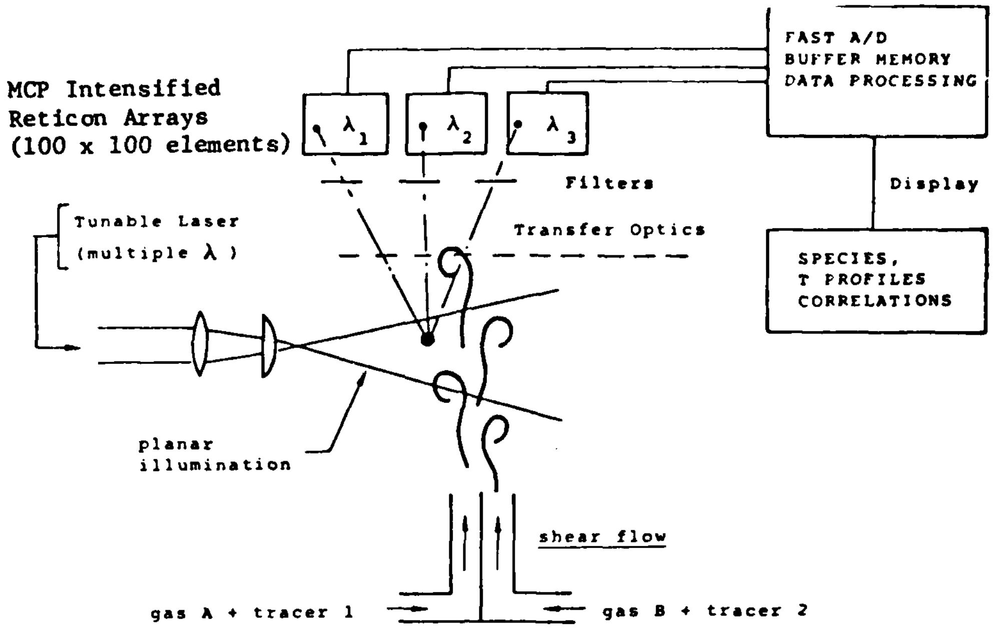
Stanford, California 94305

The utility of flow visualization in fluid mechanics is well established. At present, most visualization techniques are qualitative and are based on line-of-sight approaches poorly suited for flows with three-dimensional characteristics. With the development of laser-based light scattering techniques, it should be possible to obtain temporally resolved, quantitative records of flow properties throughout a plane (and ultimately throughout a volume) using sheet illumination and techniques such as Raman, fluorescence or Mie scattering. Pioneering work in this direction using Mie scattering from seeded particles was initiated at Yale a few years ago, and significant progress has been reported.

Work along similar lines has been initiated at Stanford during this past year. Distinguishing features of the Stanford project , as it is envisaged at present, are: (1) we plan to use techniques sensitive to species concentration (or temperature), such as fluorescence, rather than Mie scattering; (2) we hope ultimately to record at high repetition rates, thereby allowing studies of the real-time evolution of fluid mechanical structures; (3) our goal is to develop techniques suitable for combusting as well as cold flows; and (4) we plan to use an intensified photodiode array rather than a vidicon detector.

The advantages of fluorescence are that the gas can be tagged at a molecular level, thereby avoiding lag, and the signal is species specific. The major disadvantage of fluorescence has been that of properly accounting for quenching. We believe this can be handled through calibration or by using a variation of the process, known as off-resonance fluorescence, which is weaker but serves to minimize the dependence of signal level on variable quenching parameters.

The Stanford approach, as to be applied to a 2-d shear flow, is illustrated in Fig. 1. The flow will be illuminated by a sheet of light from a tunable laser source, and one or more rectangular detector arrays will be used to monitor specific species. Work is now in progress to visualize several cold flows seeded with iodine, and also to visualize species (Na and OH) and temperature in a simple laboratory combustor. Other work will include: a study of alternative forms of fluorescence, and an evaluation of systems to provide a high-repetition rate tunable laser source. Once such a source is in hand, and problems of fast data storage and transfer have been solved, we can investigate rapid scanning of the illuminated plane to yield three-dimensional recording of species concentrations. These are long-term research objectives involving several technical challenges, and hence the work is expected to require more than three years.



Objective: Develop techniques for temporally resolved 2-D and 3-D measurements of species, temperature and velocity

Status: First-generation experiments under construction
a) fluorescence from iodine in a plane; cold flow
b) fluorescence from Na, OH in a plane; hot flow

Future: Extend to: multiple species, density/temperature, and velocity; 3-d

Significance: Potential major impact on fluid mechanics

Figure 1. Quantitative flow visualization.

THREE-DIMENSIONAL FLOW VISUALIZATION.

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Stanford University
Stanford California

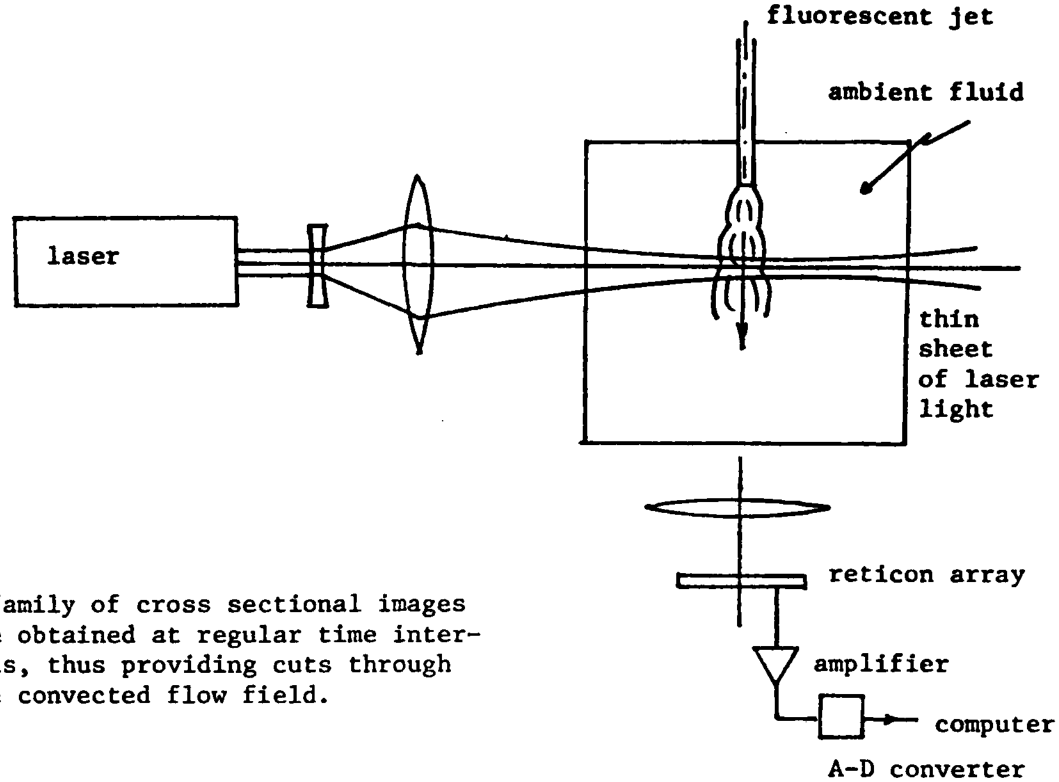
Combustion processes are inherently three-dimensional and diagnostic tools are needed which can obtain such information as species concentration, velocity or density data in a volume. In order to fully utilize the information content, the data have to be presented to a human observer with preservation of all depth cues. Features that are important, for instance for the development of new numerical codes, include topological information about various size structures in the flow and the identification of entrainment processes. This study addresses these issues and a novel diagnostic technique is applied to the study of a turbulent, coflowing jet with chemical reaction and eventually combustion.

The experimental configuration is shown in Figure 1. A sheet of laser light illuminates a cross section of the flow and excites one of the fluorescent components of the coflowing jet. The intensity of the fluorescent signal which is recorded on a reticon array is directly proportional to the species concentration and reveals information about the mixing process. By recording a family of cross sectional images at regular time intervals, a series of cuts through the three-dimensional structures, which are convected through the illumination sheet, are obtained. In other words, the three-dimensional object is sampled at a series of cross sectional planes. Using these planar images and a novel holographic technique, which is being developed as part of this research effort, the three-dimensional image can be synthesized and displayed.

The technique essentially consists of generating a hologram. The hologram can be computed by evaluating the interference pattern that results if the three-dimensional object, for which a family of cross sections are known, is illuminated by a plane wave and a point reference wave is superimposed on this object wave. The computed interference pattern can then be recorded on film to provide the hologram. An observer looking through the hologram, which is illuminated by a point reference wave, will then see the three-dimensional structures with full parallax. Only those structures that are of interest are displayed and all other information can be suppressed. This novel technique has unprecedented resolution and space bandwidth product and is applicable for the display of any kind of volumetric data which are obtained by sampling an object at planar cross sections.

The research effort started on October 1, 1981 and presently a three-dimensional test object consisting of a cube and a family of equi-spaced cross sections have been generated in the computer. The procedure for computing and generating the hologram has subsequently been applied to this object. Currently this hologram is being evaluated in order to analyze distortions associated with the hologram formation process. This knowledge will subsequently be applied to eliminate the aberrations. Future work will include the design and construction of a jet flow experiment and application of the technique to the study of volumetric entrainment processes.

DATA ACQUISITION



- A family of cross sectional images are obtained at regular time intervals, thus providing cuts through the convected flow field.

A hologram is computed from the family of cross sections and illuminated by a point light source.

DATA DISPLAY

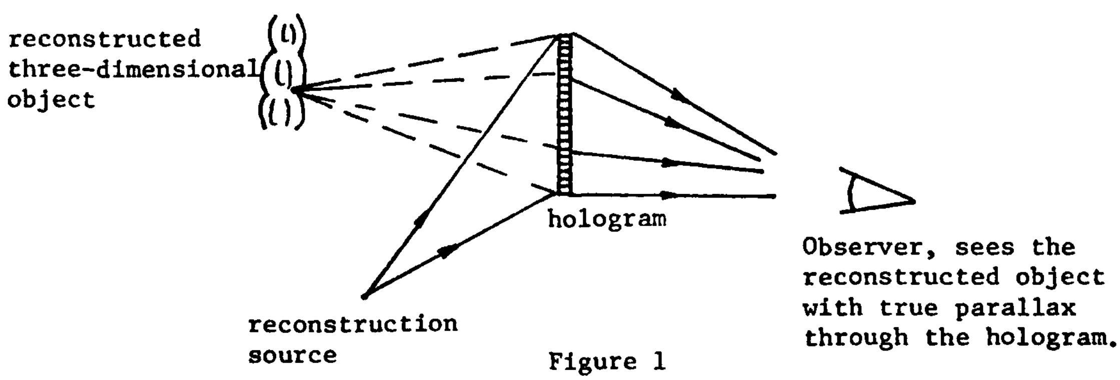


Figure 1

ACHIEVED AND ANTICIPATED SCIENTIFIC ACCOMPLISHMENTS

RESEARCH START DATE: OCTOBER 1, 1981

ACHIEVED RESULTS:

- DEMONSTRATION AND EVALUATION OF A NOVEL HOLOGRAPHIC DISPLAY TECHNIQUE USING A COMPUTER GENERATED THREE-DIMENSIONAL TEST OBJECT.

ANTICIPATED RESULTS:

EXPERIMENT: TURBULENT, COFLOWING JET WITH COMBUSTION

- QUANTITATIVE DETERMINATION OF THE THREE-DIMENSIONAL TOPOLOGY OF SMALL AND LARGE SCALE FLOW STRUCTURES.

- DETERMINATION OF THREE-DIMENSIONAL SPECIES CONCENTRATION OR VELOCITY DISTRIBUTION.

- DETERMINATION OF ENTRAINMENT PROCESSES.

Figure 2

MEASUREMENTS IN TURBULENT REACTING FLOWS

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A principal motivation for the development of advanced diagnostic techniques for reactive flows is the need to characterize flow fields in practical combustion geometries. Flow field measurements are useful not only in understanding combustor performance but also in providing information for validating combustor models. The three principal objectives of the present research effort are: (1) to develop and characterize a laboratory-scale reacting flow which simulates essential features of practical combustor flow fields, (2) to apply various diagnostic techniques in order to evaluate these techniques and (3) to obtain data on turbulent reacting flow field structure in order to guide further development of new diagnostic techniques and to provide input to reacting flow models.

The flow configuration employed in this investigation is shown in Figure 1. This unique two-dimensional reacting shear flow facility provides a means of simulating fuel-air mixing regions in air-breathing engines. A variety of probe and optical diagnostic techniques are being employed to characterize the turbulent flow field, including hot wire anemometry for time-resolved velocity measurements and fiber optic absorption probes for time-resolved species concentration measurements.

Time-resolved velocity and species concentration measurements, Figure 2, provide a complete characterization of the reacting flow, which is available for evaluation and validation of newly-developed advanced diagnostic techniques. In addition, the data provide useful new fundamental information on appropriate methods for including coupling of fluid dynamics and chemistry in reacting flow field models.

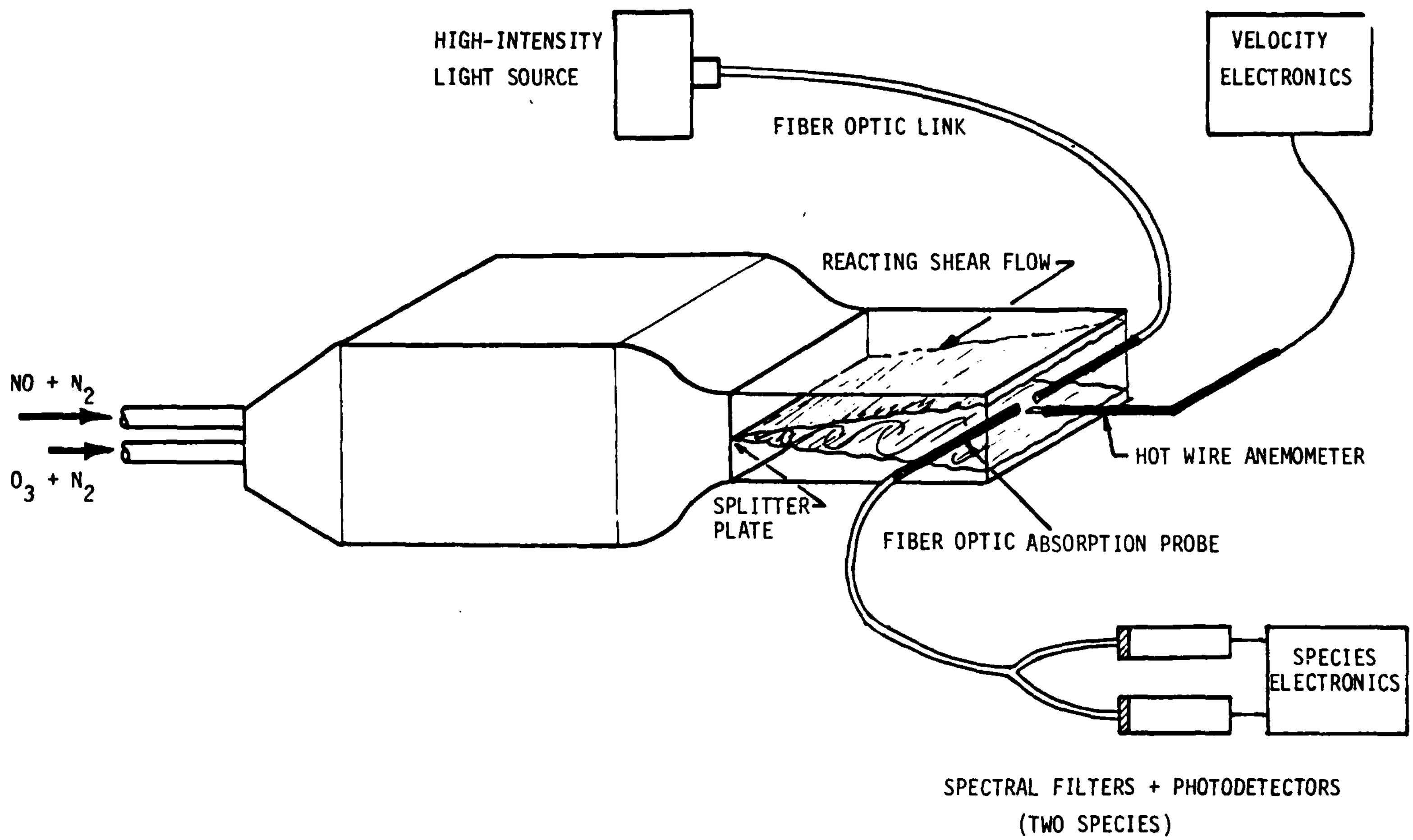

Fig. 1 - Two-dimensional Reacting Shear Flow Facility

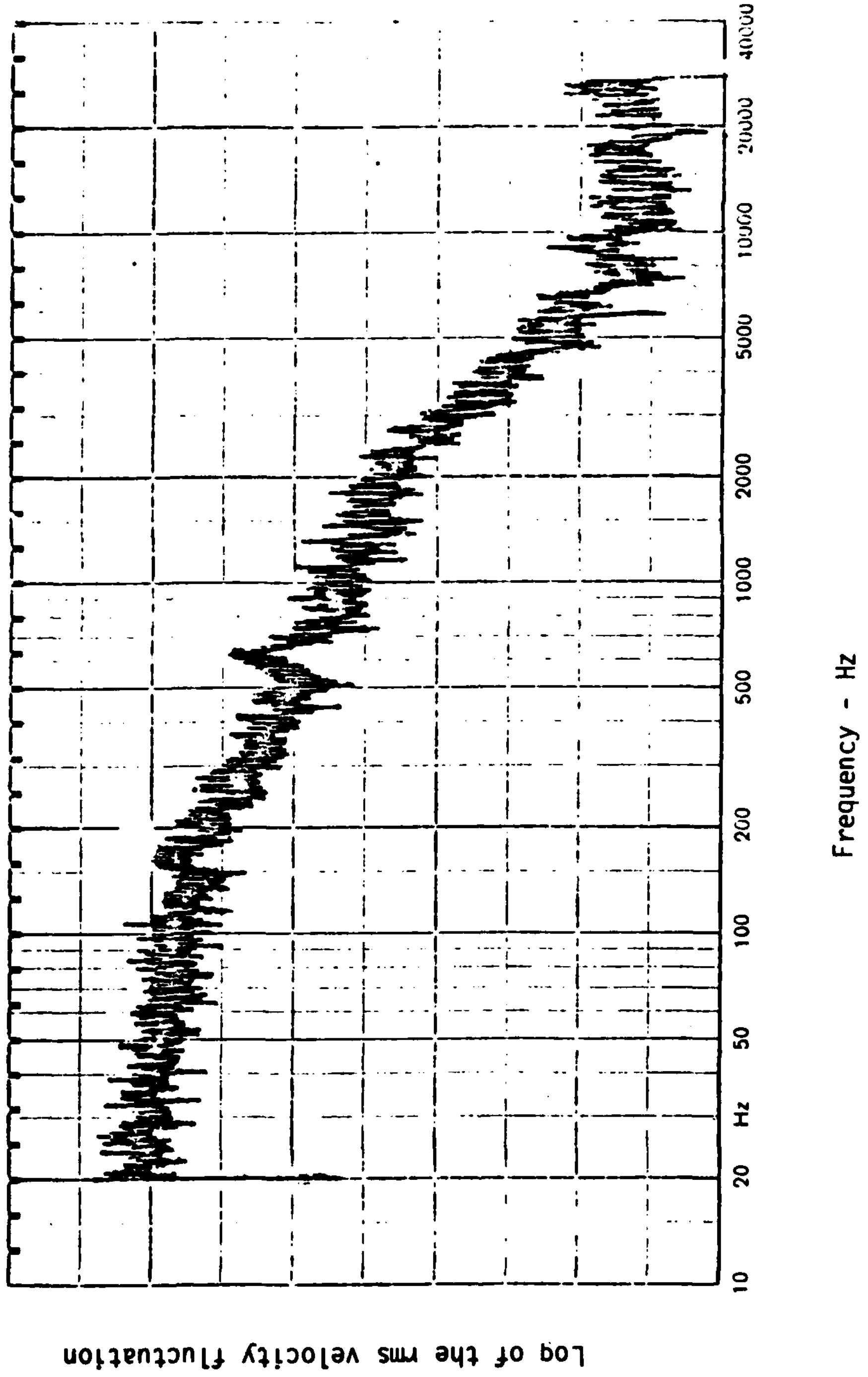

Fig. 2 - Typical Velocity Fluctuation Spectrum

AFSC – Andrews AFB Md 1982

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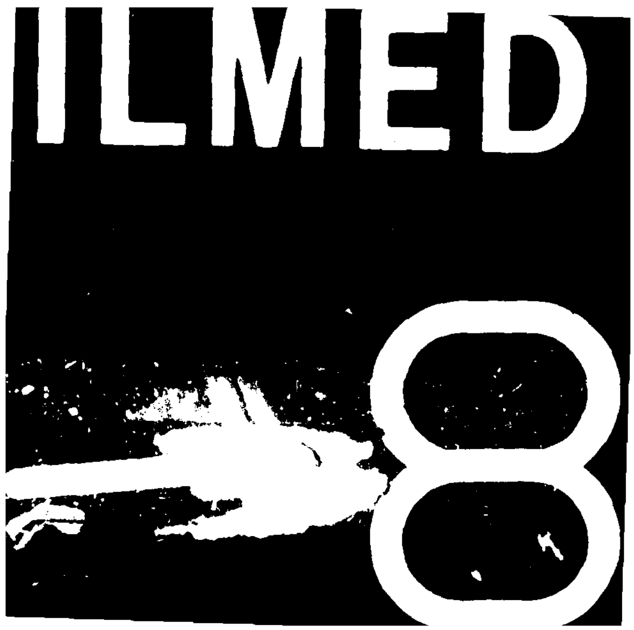
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